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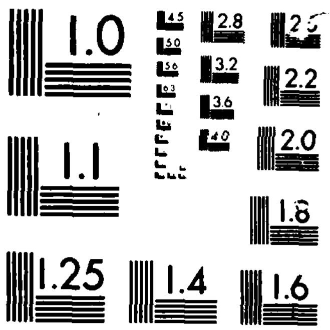

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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

Systems Technical Memorandum 86

ANALYSIS OF A MIRROR DECK LANDING AID

by

A. ROSS

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ANALYSIS OF A MIRROR DECK LANDING AID

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A. Ross

SUMMARY

The report provides details of the MDLA system, installation details and calculations concerning performance, coverage, calibration and accuracy requirements. A graphical method of presenting operational settings for height and elevation is described, as also is a simplified technique for calibration.

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PUBLICATION NOTE

The work reported here was done in the late 1970s by Mr A. Ross, when he was Group Leader of what is now Human Factors Group (HFG), in response to a Navy request for assistance with aircraft landing problems on the aircraft carrier HMAS MELBOURNE. The resulting document was intended for publication as ARL Systems Report 17 in October 1979. It had reached the page proof stage when it became clear that the carrier was to be scrapped, and further publication activity lapsed.

HFG and its predecessor groups have a long-standing interest in problems of visual perception in landing. Recently there has been renewed interest in the problems of visual approach to landing on ships because of the increasing importance of embarked helicopter operations. Examination of the proofs by Dr B.A.J. Clark, the present Group Leader of HFG, indicated much material of continuing relevance. For example, the basic optical parallax principle in the Mirror Deck Landing Aid (MDLA) is used also in the Proportional Landing System (PLS) which is currently in RAAF use for tactical landings by helicopters. Adaptation of the PLS or other visual landing aids to shipboard use would require stabilisation against ship motion, and aspects of the practical difficulties have been well covered by Mr Ross's work. Although the geometrical details of the MDLA in relation to the carrier's flight deck are now only of historical interest, the design basis of the MDLA and the methods devised by Mr Ross for MDLA alignment appear valuable in the context of current and likely future tasking on HFG.

As the type metal for Systems Report 17 had long since been re-melted, it was decided to issue the document as photocopied page proofs in the ARL Technical Memorandum series as a record of work done and in order to make the results more generally accessible within the Defence community. The document was given its present title by Dr Clark and, where possible, he made minor typographical corrections to the figures and text but the work as a whole remains almost completely in the form conceived by Mr Ross. It was impracticable to change the tenses in the text to forms which would read correctly at the time of final publication; readers should therefore bear in mind the period of the original composition and make allowance accordingly.

CONTENTS

1. INTRODUCTION

HMAS *Melbourne* is equipped with a Mirror Deck Landing Aid (MDLA) that provides a pitch stabilised visual glide slope, by which a pilot can control an aircraft on an approach to the carrier. The principal element of the MDLA is a large rectangular mirror, concave in azimuth, mounted near vertical facing aft. Powerful "source" lights mounted aft of, and directed towards, the mirror create an image in the mirror which is viewed by the pilot. The vertical position of the image in relation to a set of "datum" lights, mounted on the extended lateral centre-line of the mirror, provide the pilot with information as to whether he is above or below the nominal glide slope. A stabilisation system provides corrections of the inclination of the mirror to compensate for ship pitch so producing a pitch stabilised glide slope. There is no stabilisation in roll.

The mirror assembly has adjustments for inclination and vertical position by which the glide slope may be set in relation to the flight deck in order to achieve nominated glide slopes to specific touchdown points. The pitch stabilisation is obtained by servo-control using either an input from a suitable gyro reference, or a manual input obtained from operator tracking of the horizon through an optical sight.

The MDLA has been installed for about two decades during which time modifications have been made to change the adjustment range of mirror height, to suit different aireraft and operational conditions. It appears that currently available documentation to describe the system, its installation details and performance is rather sparse. This report brings together data gleaned from a variety of sources and also provides an analysis of the system as currently installed.

Such information as is separately available (e.g. ship drawings, operating bulletins) gives data in Imperial units. For ease of reference to such documents, and for the convenience of operators and maintainers, the master units used in this document are, therefore, Imperial units.

2. SYSTEM DESCRIPTION

The mirror assembly is mounted on a sponson on the port side of HMAS *Melbourne* at about Frame 120. The source lights are also located on the port side, at about Frame 167. The frame spacing is nominally 3 ft (ref. Drg. No. 845/51). The source lights and the centre of the mirror lie roughly in the plane of the flight deck. It is understood that two systems were installed originally, one on the port side and one on the starboard side. The starboard installation no longer exists.

The flight deck is nominally 80 ft wide and approximately 700 ft long. An extension has been built out on the port side to facilitate angled landings: the so-called "angle centre-line" being offset from the axial centre-line of the ship by about 6 degrees. The mirror and source lights are laterally offset from the angle centre-line by approximately 45 ft. There are five arrestor wires set across the deck, nominally at right angles to the angle centre-line. The general arrangement is shown in Figure 1.

A three-point mount is provided, on the sponson, for the mirror assembly. The mount is set orthogonal to the axial centre-line, not to the angle centre-line. Some adjustment, in azimuth, of the mirror assembly on the mount is possible but the range of adjustment appears insufficient to accommodate the full 6 degrees between axial and angle centre-lines. Maximum adjustment towards the direction of the angle seems to have been made, but appears to be only about $1\frac{1}{2}$ degrees, leaving the mirror axis about $4\frac{1}{2}$ degrees outboard of the angle centre-line. The stabilisation axis for pitch corrections is, in consequence, about $1\frac{1}{2}$ degrees offset from the ship lateral (pitch) axis.

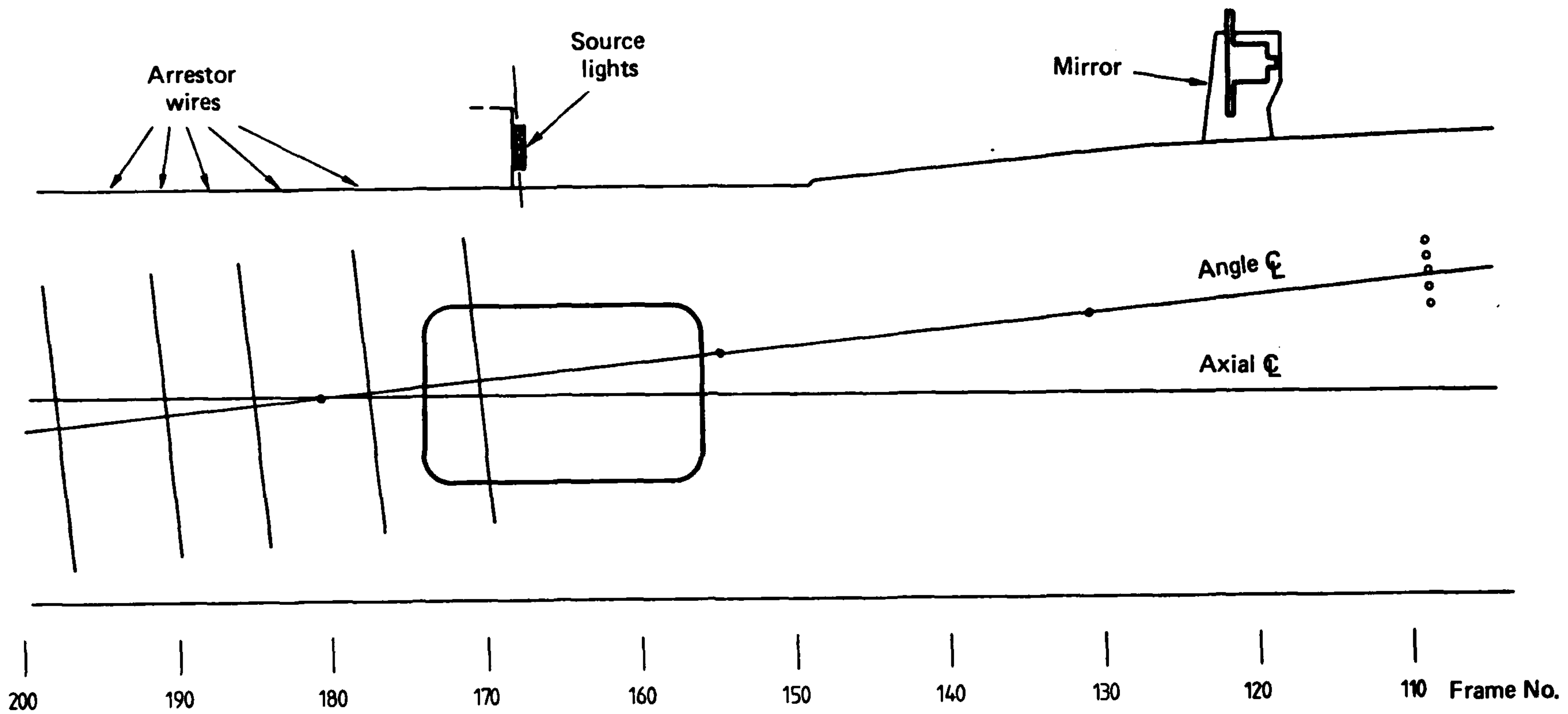


FIG. 1 MDLA GENERAL ARRANGEMENT – HMAS MELBOURNE (Scale $^{1}/_{32}'' \leftrightarrow 1'$)

The important adjustments available to the operator for selection of glide slope and touch-down point are the settings of vertical height and mirror inclination. With a fixed height setting, variation of mirror inclination will vary the elevation angle of the optically propagated glide slope. With a fixed inclination setting, variation of vertical height will offset the glide slope vertically but will also give rise to a variation in glide slope angle due to the change in relative vertical displacement of the source lights with respect to the centre of the mirror.

An additional parameter upon which the settings are dependent is the vertical displacement, for a given aircraft type, between the paths followed by the pilot's eyes and by the arrestor hook, with the aircraft at nominal approach speed and configuration.

For a nominated glide slope and specified arrestor wire the inclination and vertical height of the mirror are adjusted so that, for a "perfect" approach on the mirror, the hook will touch down 5 ft aft of the specified wire. The required settings are thus interdependent, and are also dependent on aircraft type, as discussed later.

Confirmation of operating settings is obtained *in situ* by means of "pole checks". These involve the use of a pole, of length equal to the hook-to-eye displacement, placed near vertical at the requisite hook touchdown point; i.e. at a point on the angle centre-line 5 ft aft of the specified arrestor wire. A small mirror on top of the pole is used to observe the view seen from a point on the pilot's eye path. The image of the source lights should be seen to lie on the lateral centre-line of the MDLA mirror, in line with the datum lights. Pole checks are affected by any local distortion of the flight deck in that local variation of deck height is additive to the pole height.

3. MDLA VERTICAL GEOMETRY

In this section the theoretical relationships dictating the settings of the mirror are developed. From these relationships estimates are obtained for the tolerances allowable in measuring MDLA installation details and in the pole check procedures. The vertical geometry (not allowing for the lateral displacement from the angle centre-line of the mirror and source lights) is shown in Figure 2.

The relative heights of the flight deck, mirror and source lights are important to the determination of settings. The flight deck on HMAS *Melbourne* has become locally distorted over the years and a reference plane has been defined, for measurement purposes, by three points chosen where the deck is stiffened by vertical support structure below (the hangar walls). Vertical setting of the mirror is made by reference to graduations on a scale set in the mirror assembly. The vertical height, with respect to the deck reference plane, of the mirror datum corresponding to the zero of the scale must be determined by measurement. This is made difficult by the fact that scale zero is not an achievable setting due to "bottoming" of the mirror housing on the support structure.

In the analysis below, for convenience in the analytical development and because of the difficulty of defining a deck plane, the datum point is taken to be the centre of the source lights, with vertical heights taken normal to a plane through the source lights parallel to a "mean deck plane". The "mean deck plane" *vis-à-vis* the three reference points will be discussed later.

The inclination setting of the mirror is set also by reference to a scale within the mirror assembly. The scale is graduated for glide slope angle increments rather than inclination angle (2:1 ratio). The relative angle, with respect to the mean deck plane, of the normal to the mirror face corresponding to the zero of the scale, must also be established by measurement.

The following parameters are therefore defined (see also Fig. 3) for development of the analysis:

H_0	Height of mirror, at zero scale setting, above source lights.
H_S	Height of mirror above zero setting (scale reading).
$H_M = H_S + H_0$	Height of mirror above source lights.
H_D	Height of deck above source lights (actual value < 0).
H_Y	Height of pilot's eye path above arrestor hook path (hook–eye height).
D_L	Distance between mirror and source lights.
D_W	Distance between mirror and arrestor wire.
D_T	Distance between mirror and hook touchdown point.

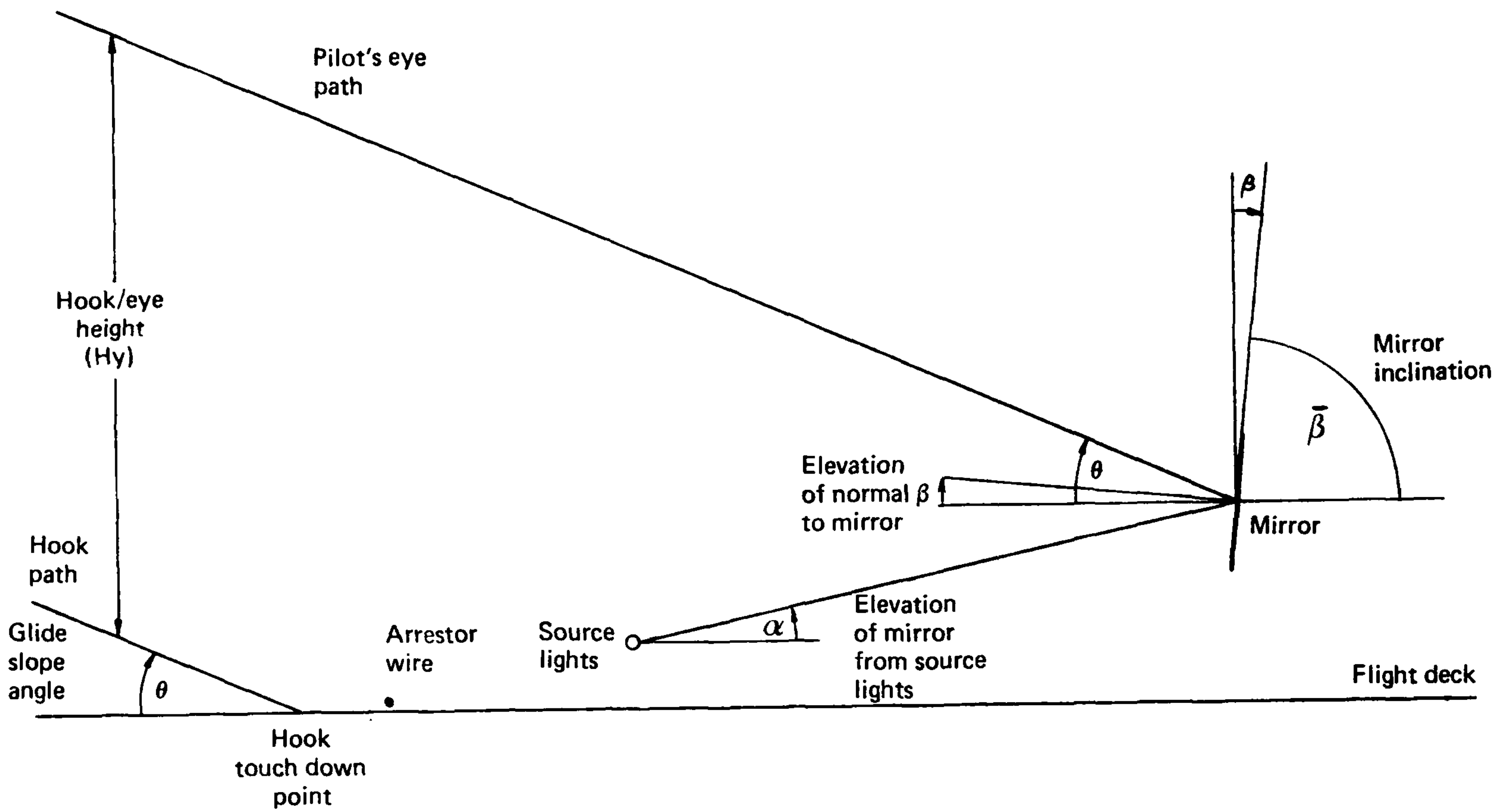


FIG. 2 MDLA VERTICAL GEOMETRY

α_M	Elevation of mirror centre from source lights.
β_0	Elevation of normal to mirror face, at zero angle setting.
β_S	Elevation of normal to mirror, relative to zero setting (scale reading ÷ 2).
$\beta_M = \beta_S + \beta_0$	Elevation of normal to mirror.
$\beta_M = 90° - \beta_M$	Inclination of mirror.
θ	Glide slope angle.

The basic relationships (from Fig. 3) are:

$$H_M = D_L \tan \alpha_M$$
$$\alpha_M + \beta_M = \theta - \beta_M$$
$$H_M + D_T \tan \theta = H_Y + H_D.$$

Hence, given a required glide slope angle (θ), arrestor wire (D_W), and aircraft type (H_Y), the mirror settings (H_S, β_S) for the hook touchdown point to be 5 ft aft of the wire ($D_T = D_W + 5$), are given by:

$$H_S + H_0 = H_M = H_Y + H_D - (D_W + 5)\tan\theta$$
$$\beta_S + \beta_0 = \beta_M = \tfrac{1}{2}[\theta - \tan^{-1}(H_M/D_L)].$$

The relationships between H_M, β_M, D_T and θ may be plotted in several ways. Noting that both equations contain H_M and θ, a particularly convenient plotting format is obtained by using a rectilinear co-ordinate system of $\{\theta, H_M\}$ and plotting intersecting loci of constant values of β_M and D_T using:

$$H_M = D_L \tan(\theta - 2\beta_M)$$
$$H_M = (H_Y + H_D) - D_T \tan\theta.$$

Adjustment of the sets of loci, with respect to one another, by adjustment in the direction of H_M can be used to accommodate any value of H_Y. The two sets of loci may then be used to determine settings for any combination of aircraft type, glide slope angle and hook touchdown point.

With the small angles involved for θ and β_M a further simplification can be made by linearising the loci. The simplest form of linearisation is to use the approximation:

$$\tan\phi \simeq \phi \text{ (radians)}.$$

Errors resulting from that approximation, for angles up to the maximum glide slope angle, θ, of $4\frac{1}{2}$ degrees are negligibly small (although greater accuracy can be obtained, if required, by linearising the D_T loci in particular across the band of interest from $3\frac{1}{2}$ to $4\frac{1}{2}$ degrees).

Using the simple approximation for tan and converting from radians to degrees, the β_M loci are developed from

$$H_M = D_L(\theta - 2\beta_M)\pi/180$$

by parametric variation of β_M. For equal increments of β_M the loci are equi-spaced parallel straight lines with slope proportional to D_L. A set of such loci are plotted in Figure 4 using a value for D_L of 143·239 ft. This value, which is close to the actual value, has a particular significance because of the simple working relationship that stems from it, viz: that to maintain a given glide slope as H_M is changed, the compensating change required in β_M is 1 minute of arc in β_M per 1 inch in H_M. The particular value results directly from the above equation via

$$\Delta H_M = -2D_L \frac{\pi}{180} \Delta\beta_M \qquad \text{for } \theta = \text{constant}.$$

A value of 143 ft for D_L, the distance from mirror to source lights, can be found in some early MDLA documents and it seems probable that this was an original design value. This is supported to some extent by the fact that the graduations on the height and angle scales within the MDLA assembly correspond to increments of 3 inches in H_M and 3 minutes of arc in β_M (6 minutes of arc, 0·1 degrees, in θ). For values of D_L close to, but not exactly, 143·239 ft the "equal increment" relationship is still useful.

Similarly the D_T loci are developed from

$$H_M = (H_Y + H_D) - D_T\,\theta\,\pi/180$$

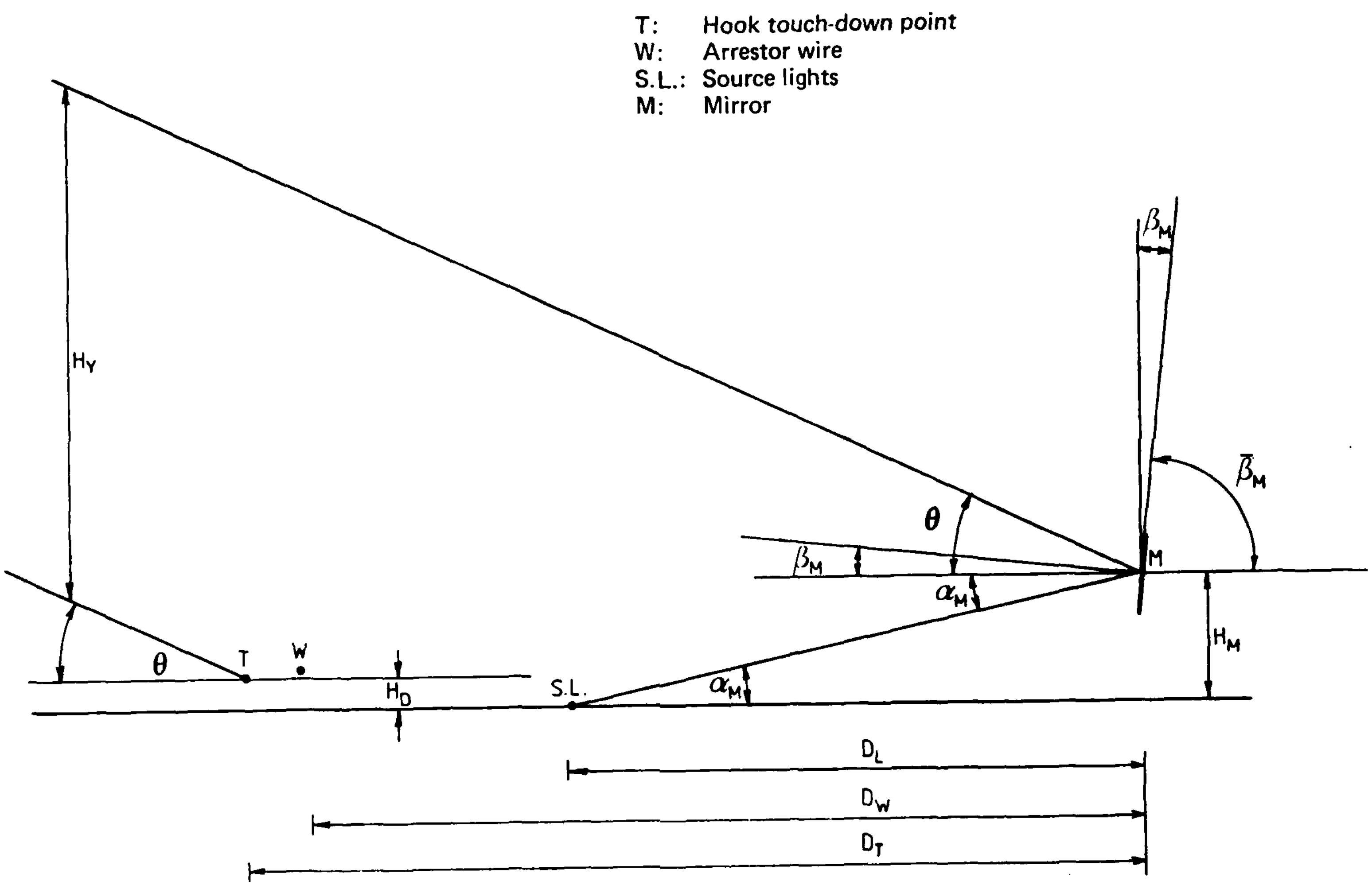


FIG. 3 MDLA PARAMETER RELATIONSHIPS

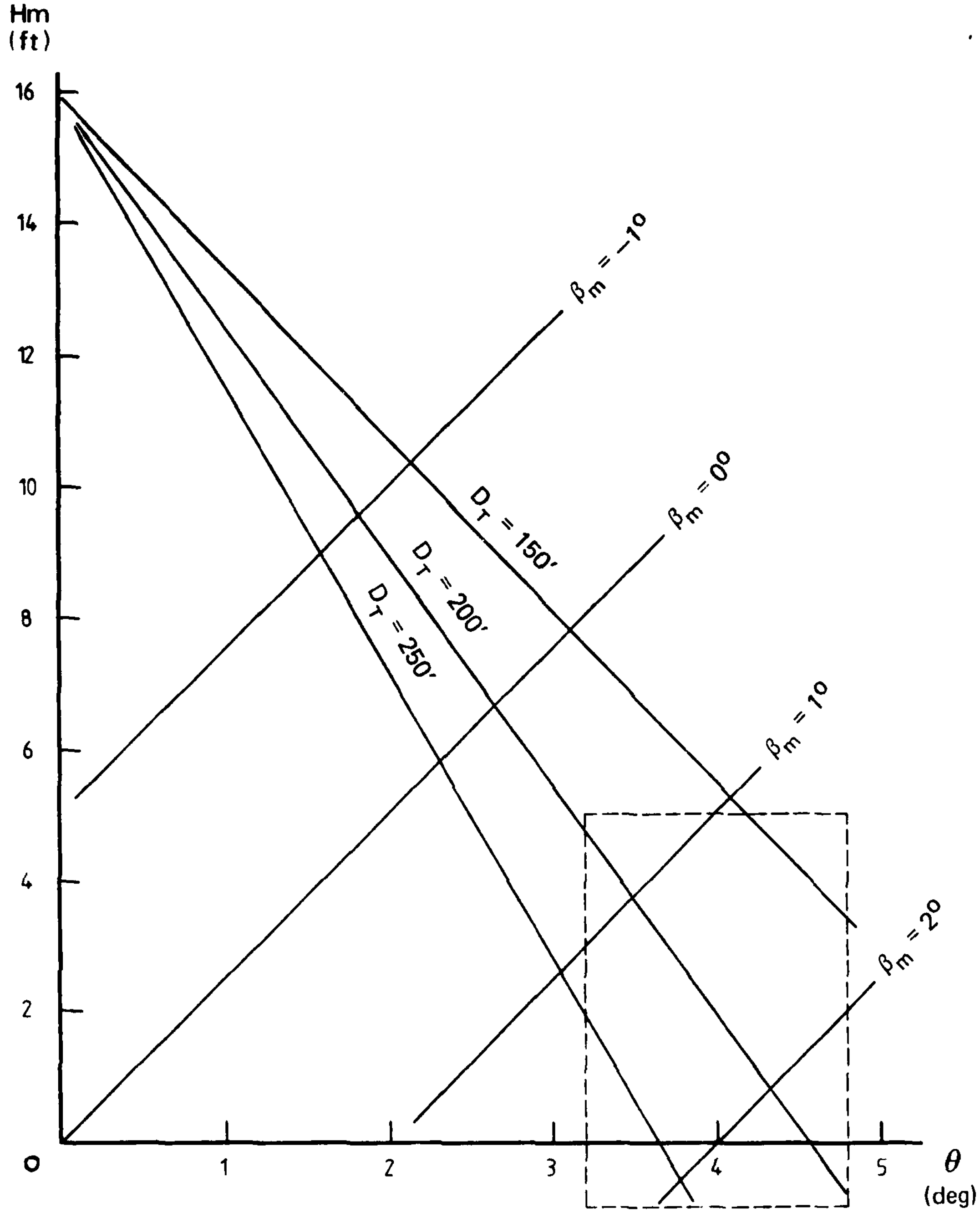


FIG. 4 THEORETICAL MDLA CHARACTERISTICS

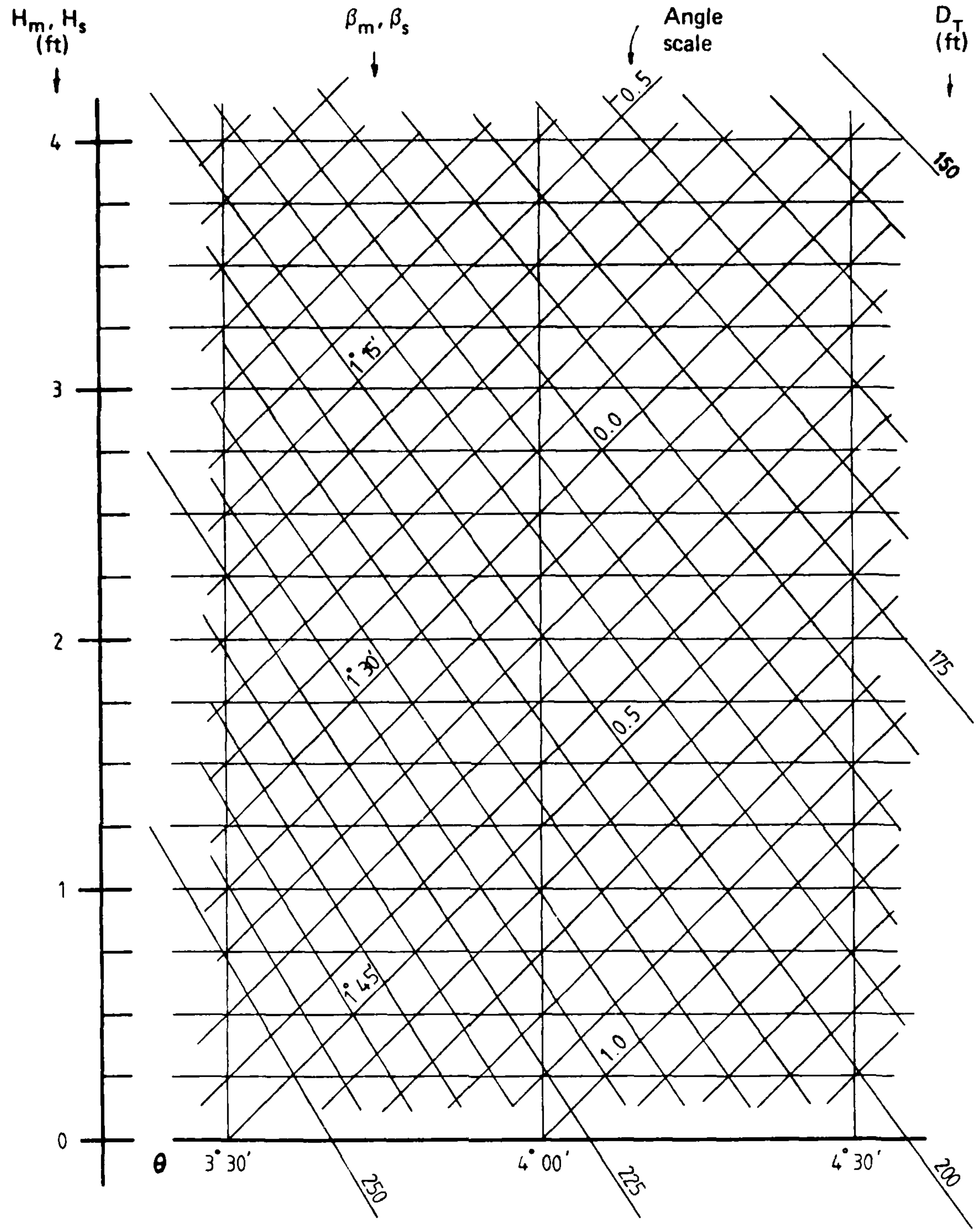


FIG. 5 THEORETICAL MDLA CHARACTERISTICS:Working range

by parametric variation of D_T. These are a set of straight lines, with slopes proportional to D_T, radiating from a point on the H_M axis at value $(H_Y - H_D)$. A set of such loci are also plotted in Figure 4 using a value for $(H_Y - H_D)$ of 16 ft. For different values of H_Y the set would be displaced up or down the H_M axis. Plotting the set corresponding to the specific values of D_T, corresponding to the arrestor wires, on a transparent overlay would permit adjustment for any value of H_Y.

The region of specific interest is that shown in Figure 4 by the dotted box encompassing values of θ from $3\frac{1}{2}$ to $4\frac{1}{2}$ degrees and values of D_T from 150 to 250 ft, with settings of H_M from 0 to 4 ft and β_M from 1 to 2 degrees.

To establish operating settings in terms of MDLA scale graduations (H_S, β_S) the values of β_0, H_0, H_D and D_L must be found by measurement on the actual installation, in addition to the D_W value for each arrestor wire. H_Y values must also be determined for each aircraft type.

The installation values of H_0 and H_D are close to zero and that for β_0 is approximately $1^\circ 30'$. Again it seems probable that these are original design values for the MDLA system such that with the source lights and mirror zero setting coplanar with the flight deck, a 3 degree glide slope would be propagated for a zero angle setting.

The theoretical plot of operating settings corresponding to those assumed design values is shown in Figure 5. Choosing scale units of 3 inches for H_M and 6 minutes for arc of θ results in the β_M loci lying at 45 degrees to the axes. Also plotted are D_T loci for values of D_T from 150 to 250 ft at intervals of 5 ft. The specific values used to generate Figure 5 are

$H_0 = 0$ (i.e. $H_M = H_S$)
$H_D = 0$
$H_Y = 16$ ft
$D_L = 143{\cdot}239$ $(180/2\pi \times 60/12)$
$\beta_0 = 1^\circ 30'$.

The accuracies required in settings, and/or in basic measurements is implicit in the diagram. Tolerances in the determination of installation values for H_0, H_D, D_L, D_W and β_0, and for the estimated H_Y values for each aircraft, should ideally be equivalent to about one order smaller than the scale graduation intervals, i.e.

H_0 $\pm 0{\cdot}3$ in. say $\pm 0{\cdot}5$ in.—nearest inch,
H_D $\pm 0{\cdot}3$ in., say $\pm 0{\cdot}5$ in.—nearest inch,
H_Y $\pm 0{\cdot}3$ in., say $\pm 0{\cdot}5$ in.—nearest inch,
D_L $\pm 0{\cdot}3$ in. $\times$ (143 ft/4 ft) $= \pm 10{\cdot}7$ in., say $\pm 1{\cdot}0$ ft—nearest 2 ft,
D_W $\pm 0{\cdot}3$ in. $\times$ $(1/\tan 4\frac{1}{2}^\circ)$ $= \pm 3{\cdot}8$ in., say $\pm 0{\cdot}5$ ft—nearest foot.

The accuracy and tolerances associated with pole checks also require examination. The pole check geometry is shown in Figures 6 and 7. The relative effects of errors in pole height (H_Y), mirror height (H_M) and mirror inclination (β_M) in setting up a pole check, may be estimated by calculating the resulting displacements of the image on the face of the mirror as seen from the viewing point. It is also useful to relate these displacements to the span of the image as seen from the viewing point.

From Figure 6, with the vertical span of the source lights taken to be h ft, and again using small angle approximations, then:

(i) The angle ϕ subtended by the image at the viewing point is given by

$$\phi = (h/D_T + D_L) \text{ (radians)}.$$

(Note that in Figure 6, and hence in the above expression, the observer's eye is assumed to be at the viewing point at the top of the pole. In fact the observer's eye is about 10 ft below the top of the pole and the denominator term should strictly be $D_T + D_L - 10$. With $D_T \simeq 200$ and $D_L \simeq 143$ the error in the denominator term is about 3%. In view of the fact that this expression, and others to follow, are being used only to estimate tolerances, that inaccuracy in estimating tolerances is acceptable.)

(ii) The vertical span, H_I, of the image subtended on the face of the mirror is given by

$$H_I = D_T\phi = (D_T/D_T + D_L)h \text{ (ft)}.$$

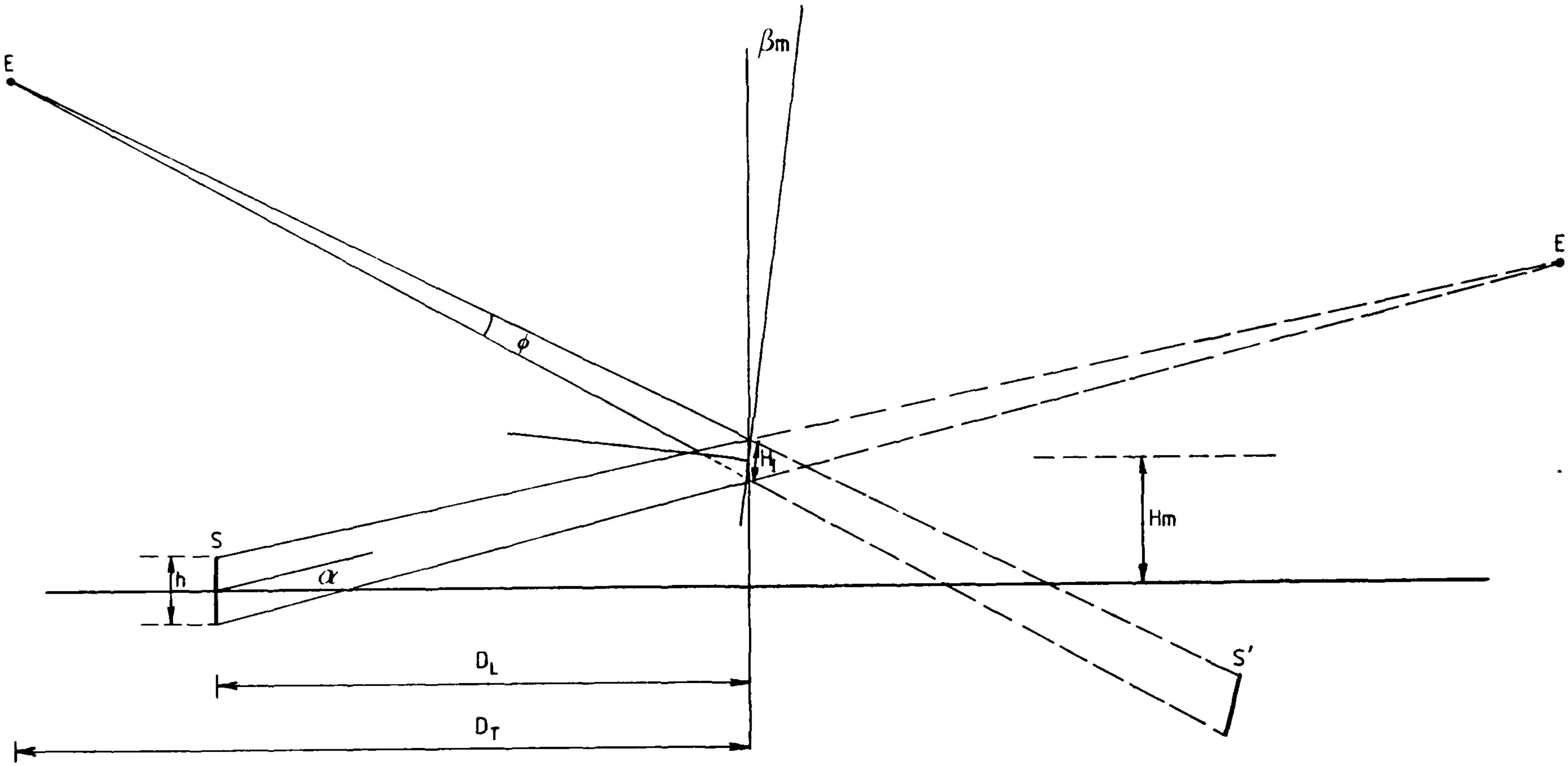


FIG. 6 POLE CHECK GEOMETRY – IMAGE SPAN

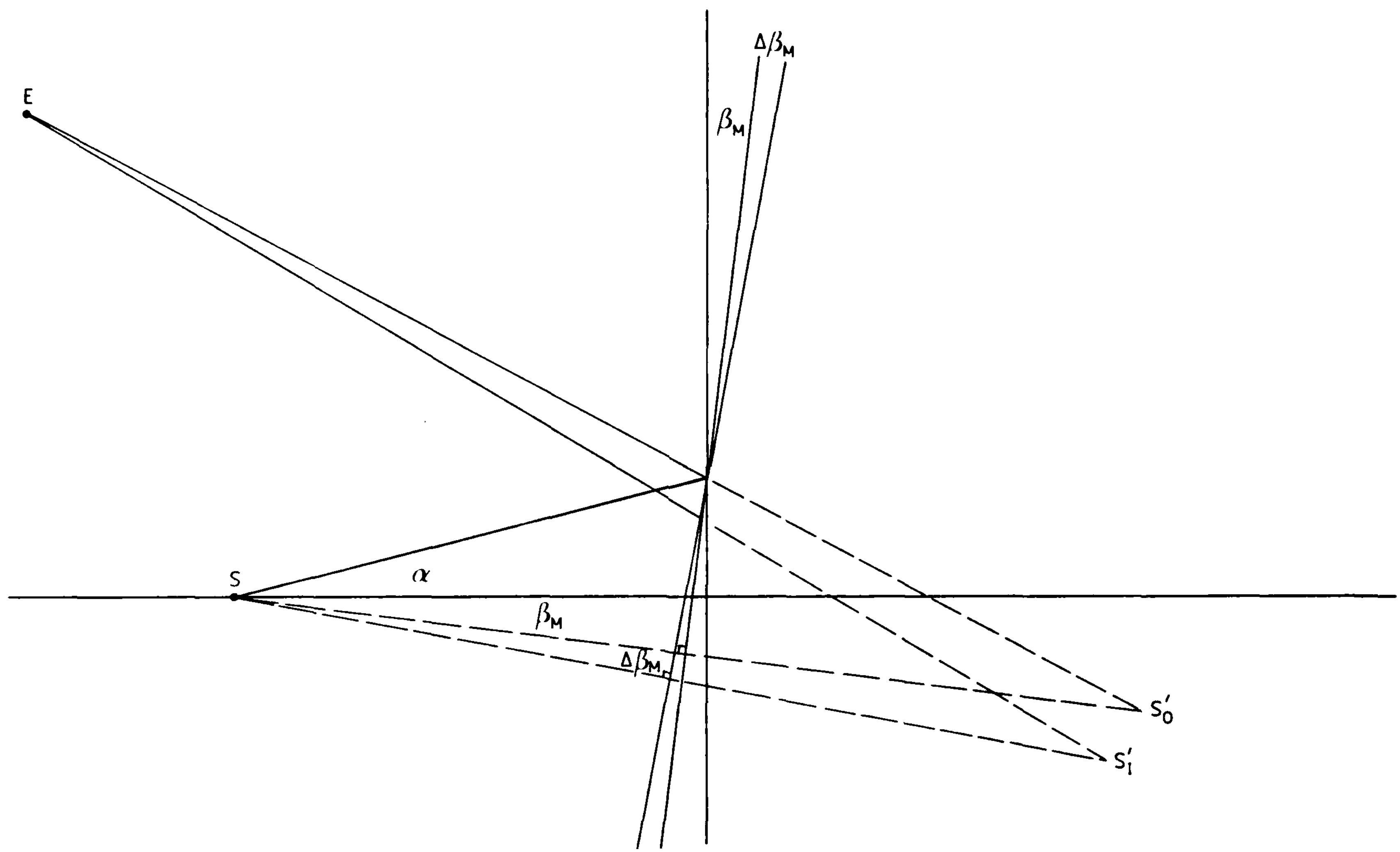


FIG. 7 POLE CHECK GEOMETRY – INCLINATION ERROR

(iii) For an error of ΔH_Y in pole height setting the displacement δ_Y of the image on the face of the mirror is given by

$$\delta_Y = (D_L/D_T + D_L)\Delta H_Y \text{ (ft)}.$$

(iv) For an error of ΔH_M in mirror height setting the displacement δ_M of the image on the face of the mirror is given by

$$\delta_M = \Delta H_M \text{ (ft)}.$$

And, from Figure 7:

(v) For an error of $\Delta\beta_M$ in mirror angle setting the displacement δ_β, of the image on the face of the mirror is given by

$$\delta_\beta = (D_T/D_T - D_L)2D_L\,\Delta\beta_M \text{ (ft)}, \ (\Delta\beta_M \text{ in radians}).$$

The vertical span of the source lights is approximately 0·9 ft (documented 10½ in.) and taking a mid-position value of 200 ft for D_T together with 143·239 ft for D_L the above expressions give

$\phi = 0{\cdot}15$ degrees
$= 9$ minutes of arc
$H_I = 0{\cdot}52$ ft
$= 6{\cdot}3$ in.
For $\Delta H_Y = 3$ in.
$\delta_Y = 1{\cdot}25$ in.
For $\Delta H_M = 3$ in. (1 scale interval)
$\delta_M = 3$ in.
For $\Delta\beta_M = 3$ min. of arc (1 scale interval)
$\delta_\beta = 1{\cdot}75$ in.

The equivalence

$$1 \text{ min. of arc } (\beta_M) \Leftrightarrow 1 \text{ in. } (H_M)$$

is not preserved under these conditions because the glide slope is not held constant.

Thus errors equivalent to 3 minutes of arc in β_M (1 scale interval) arise from 1·75 in. in H_M (0·6 scale interval) or 4·2 in. in H_Y. It follows that if pole checks are expected to confirm the repeatability of setting in β_M then the required accuracy in the setting of H_M and H_Y should be near $\pm$0·25 in. (0·1 scale interval) in H_M and $\pm$0·5 in. in H_Y.

It should be noted that in the above analysis the ship's frame has been taken to be static. The analysis relates to mirror settings and calibration. In operational conditions other effects, not covered in this document, give rise to degraded performance. The stabilisation system provides corrections to stabilise the glide slope *angle*, but the secondary effects of longitudinal and vertical changes of position of the mirror with respect to the ship's centre of pitch and roll remain uncorrected. Similarly, ship heave causes vertical displacement of the glide slope, for which there is no compensation. It should be noted that ship speed results in an aircraft flight path angle that is less than the nominal glide slope angle.

4. MDLA INSTALLATION DATA

The data given in this section have been acquired from various sources and fall in five categories, viz.:

(i) scaled from Drg No. 845/51 Sht 3, 30 January 1969 (using interpolation between "Frames" where applicable);
(ii) "as fitted" 1955 details;
(iii) G.I.D. measurements, May 1969;
(iv) G.I.D. measurements, May–July 1976;
(v) direct observation/measurements by the author.

The most comprehensive set of data available to the author on *in situ* measurements and derived mirror settings is that contained in the enclosures to Reference 2, GMGID letter DNC 20-14-92 (undated, *c*. July 1976) to DMED and DNAP, referred to above as (iv) *G.I.D.* measurements May–July 1976.

Multiple measurements are given below wherever possible in order to show the degree of consistency or variation.

4.1 Plan Position of Centre of Mirror Surface

(*a*) Drg. 845/51:	Frame 121$\frac{2}{3}$	365′ (from ship datum)
	Offset from axial ℄	63′ Port
	Offset from angle ℄	45′ Port
(*b*) G.I.D. 1976:	Offset from angle ℄	44′9$\frac{3}{16}$″ Port

4.2 Plan Position of Centre of Source Lights

(*a*) Drg. 845/51:	Frame 167$\frac{2}{3}$	503′ (from ship datum)
	Offset from axial ℄	48′ Port
	Offset from angle ℄	44$\frac{1}{4}$′ Port
(*b*) G.I.D.:	Offset from angle ℄	44′ Port

4.3 Distance: Source Lights to Mirror (D_L)

(*a*) Drg. 845/51 (calculated from 4.1(*a*), 4.2(*a*) above):	138·8′
(*b*) As fitted 1955:	143′
(*c*) G.I.D. 1969:	137′

4.4 Intersection of Angle C with Axial ℄

(*a*) Drg. 845/51 Frame 179 537′ (from ship datum)

4.5 Angle between Angle ℄ and Axial ℄

(*a*) Drg. 845/51: 5·85°

(*b*) "Reputation": 6°

4.6 Intersection of Arrestor Wires with Axial ℄

(*a*) Drg. 845/51:	Wire No. 1	Frame 197·90
	2	190·75
	3	184·85
	4	177·30
	5	170·20
	(Round-down)	218

4.7 Distance: Arrestor Wires to Mirror, along Angle ℄ (D_W)

Wire No.	(*a*) Drg. 845/51 (using 4.6)	(*b*) As fitted 1955	(*c*) G.I.D. 1969	(*d*) G.I.D. 1976
1	233·9′	233′	231·33′	233′4$\frac{1}{2}$″
2	212·5′	212′	210·33′	212′6$\frac{1}{2}$″
3	195·0′	195′	193·00′	195′0$\frac{7}{8}$″
4	172·4′	173′	170·50′	172′8$\frac{3}{8}$″
5	151·2′	151′	149·33′	151′7$\frac{1}{2}$″
(Round-down)	293·9′		293·00′	

4.8 Mirror Dimensions

(*a*) Direct measurement	Height:	1·2 m (47·24" ≃ 4')
	Width:	1·5 m (59·06" ≃ 5')
	Depth of curve:	93 mm
(*b*) Specification	Height:	4'
	Width:	5'

4.9 Mirror Radius of Curvature

(*a*) By calculation from depth of curve:	3·07 m (10·07')
(*b*) By direct observation of images:	3 m (9·84')
(*c*) Specification:	10'

4.10 Relative Heights: Flight Deck/Mirror/Source Lights

As discussed in Section 3, the relative heights of the flight deck, mirror zero setting and source lights are important in the determination of operating settings. The flight deck itself has local distortions but for reference and measurement purposes a "deck plane" has been defined by three points chosen where the deck is stiffened by vertical support structure below. These points are nominally 26 ft offset from the axial centre-line, on the port side at Frames 195 and 174, and on the starboard side at Frame 174 (points A, B and C in Fig. 12).

Measurements made at G.I.D. in 1976 are given below. The precise method of measurement used is not known. Dimensions are given with respect to the reference "deck plane" defined by the three points.

4.10.1 Flight Deck

Level of flight deck, on the angle centre-line, at points 5 ft aft of each arrestor wire:

Wire No. 1	· $\frac{1}{2}$"
2	$\frac{3}{4}$"
3	1$\frac{3}{4}$"
4	1$\frac{15}{16}$"
5	· $\frac{15}{16}$"

4.10.2 Mirror

Level of centre of mirror aperture and level of the extended lateral centre-line of the datum lights (G.I.D. 1976):

Centre of mirror: 9$\frac{7}{8}$"
Datum lights: · 9$\frac{1}{8}$"

Note: The vertical height setting of the mirror at which this measurement was taken is not specified in the Reference 2 enclosures. However, Enclosure 2 states that:

Mirror height   scale height · 0·76 ft

and the 0·76 ft corresponds to the · 9$\frac{1}{8}$ in. height of the datum lights. The implication is that the mirror was set to a vertical height setting of zero scale reading. How this was arranged, in view of the fact that for normal operation zero scale reading is not achievable due to "bottoming" of the mirror housing on the support structure, is not known. If in fact the housing was "bottomed" and the scale reading was not zero then an error exists. This point is discussed also in Section 5.

4.10.3 Source Lights

Four source lights are installed, each with diameter 10$\frac{1}{2}$ in., at a spacing of 22 in. between centres. This extended lateral span of the source lights compensates for the azimuthal compression of the image when viewed through the concave mirror and restores width to the image.

The level of the centre of each of the four source lights is (G.I.D. 1976):

No. 1	$+9\frac{7}{8}''$
2	$+9\frac{3}{4}''$
3	$+9\frac{3}{4}''$
4	$+10''$.

Note: Enclosure 2 to Reference 2 gives the level of the source lights as 0·714 ft, corresponding to $8\frac{9}{16}$ in. The basis of this discrepancy is not known. This point is also discussed in Section 5.

4.11 Hook-to-Eye Heights (H_Y)

Hook-to-eye heights for the S-2E and the A-4G are given in various G.I.D. and Navy Office documents as:

S-2E	16·5′
A-4G	15·5′.

The basis and original source is not known. It would appear, however, that they have been estimated only to the nearest 0·5 ft rather than to the nearest 1 in. as suggested in Section 3.

5. 1976 OPERATING SETTINGS

The theoretical mirror settings generated from the G.I.D. 1976 data given in Section 4 are tabulated in Reference 2, Enclosure 2. Table 1 together with the corresponding measured values of β_M obtained from pole alignment procedures. The precise method of derivation of the theoretical values is given in Reference 2 and for that reason the "theoretical" and "measured" values are particularly useful for comparison with one another and with the graphical plotting method of Section 3.

One minor aspect of the selection of settings requires explanation. Due to the greater forces, loads and friction of the vertical adjustment system it is more difficult to obtain fine adjustment in height than it is in angle. For this reason it has become the practice to use only height settings that correspond to scale graduation marking ($\frac{1}{4}$ ft in H_S) but to use angle settings that might require interpolation between scale graduations, at least to the half interval positions (corresponding to 1·5 min. of arc in β_S or 3 min. of arc, 0·05 degree, steps in θ). The theoretical settings are arranged to correspond with an exact hook touchdown point, and thus pole check site, rather than an exact glide slope. The height graduation setting is chosen as the one giving the glide slope closest to, but not less than, the nominal glide slope. Nominal glide slopes are $3\frac{1}{2}$, 4 and $4\frac{1}{2}$ degrees.

To generate the appropriate graphical plots the following data, consistent with that used to generate the "theoretical" values, were used:

$H_0 =$	$+0·5''$	$(0·76–0·714' = 0·045' = 0·55'')$		
$H_D =$	$-8·5''$	$(0·714' = 8·57'')$		
$H_Y =$	16·5′	(S-2E)		
	15·5′	(A-4G)		
D_L	137′			
$D_W =$	233·5′	$\Delta H_W =$	$+\frac{1}{2}''$	No. 1 wire
	212·5′		$-\frac{3}{4}''$	2
	195·0′		$-1\frac{3}{4}''$	3
	172·5′		$2''$	4
	151·5′		$+1''$	5.

The resulting plots, incorporating appropriate adjustments for H_0, H_D, H_Y and the variations in flight deck level are shown in Figure 8 for S-2E and Figure 9 for A-4G. For each arrestor wire a set of three loci is plotted, representing:

(i) the wire itself, at mean deck height;
(ii) the point, at mean deck height, 5 ft aft of the wire;
(iii) (ii) corrected for flight deck level errors.

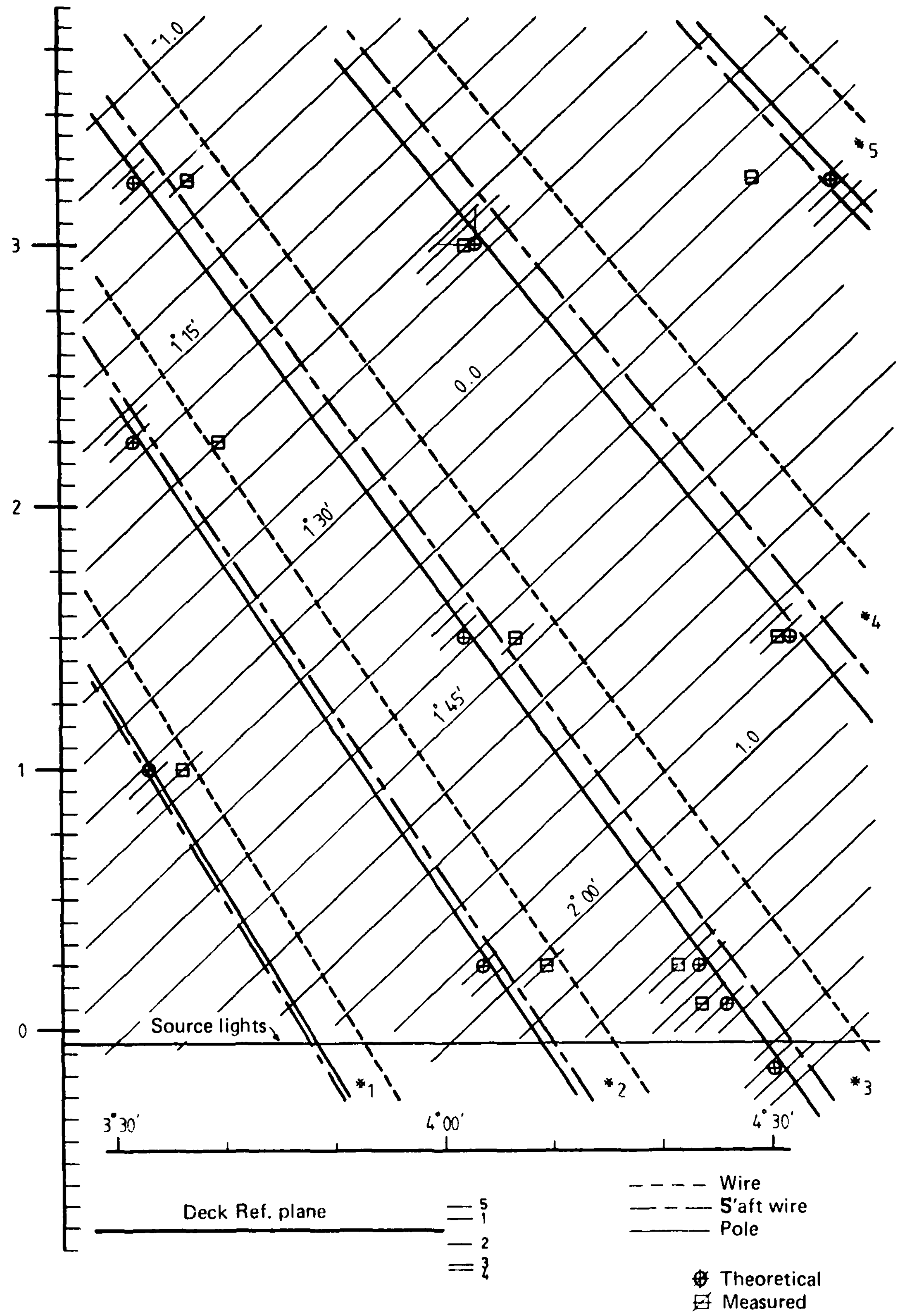


FIG. 8 1976 OPERATING SETTINGS, S – 2E

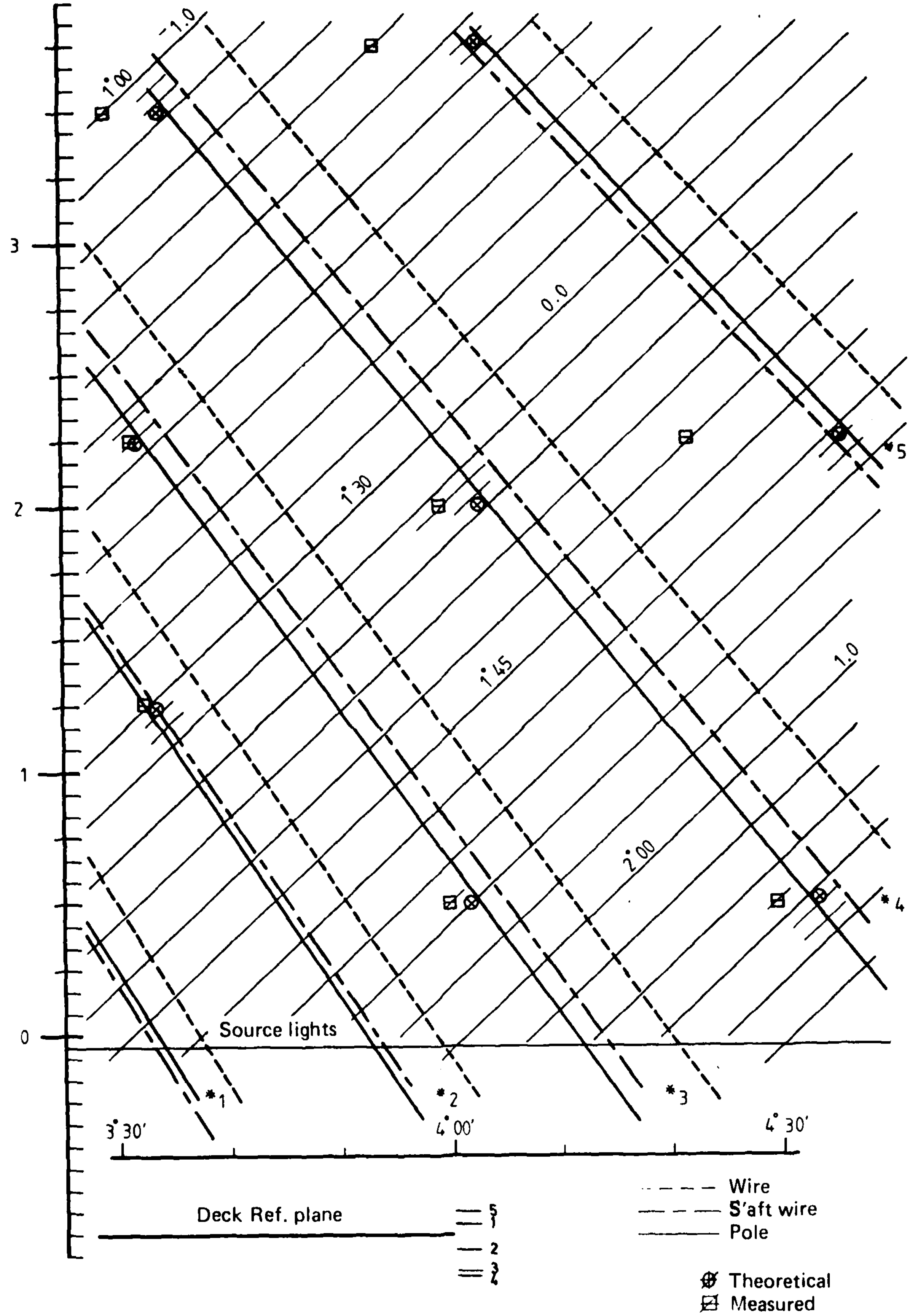


FIG. 9 1976 OPERATING SETTINGS, A – 4G

Also plotted on Figures 8 and 9 are the "theoretical" and "measured" values from Reference 2. Two of the "theoretical" values appear to have been calculated incorrectly. That for S-2E, 4 degree glide slope to No. 4 wire is based on an incorrect calculation of α. That for A-4G, $3\frac{1}{2}$ degree glide slope to No. 2 wire appears to be based on a $+\frac{1}{2}$ in. (No. 1 wire) deck error instead of $-\frac{3}{8}$ in.

With due allowance for these two values, the plotted theoretical points lie slightly below their relevant D_T loci. This is due to the small systematic error in the plot arising from the small angle approximation used to generate the D_T loci. The error is maximum at the bottom right-hand corner of the plot, corresponding to the largest value of $D_T \tan\theta$. For the No. 3 wire at a glide slope of $4\frac{1}{2}$ degrees the error is

$$200(\tan 4\tfrac{1}{2} - 4\tfrac{1}{2} \times \pi/180)\ \text{ft} = 0{\cdot}032\ \text{ft} = 0{\cdot}39\ \text{in.}$$

The high resolution available from the plotting method is apparent. As originally drawn the scale of the plot was 1 mm for 0·25 in. in H_M and 0·05 degrees in θ.

Some measured values are extremely close to their theoretical equivalents while others are significantly different: the maximum being 7 minutes of arc in β_M for the case of A-4G, $4\frac{1}{2}$ degree glide slope to No. 5 wire. The deviation appears to become progressively greater as distance from the mirror reduces. This is consistent with a reducing sensitivity of the pole check procedure but also involves observing the image further off the vertical centre-line of the mirror. In fact, for the No. 5 wire pole check the image is close to the far edge of the mirror. The quality of the mirror reflecting surface in terms of local variation from nominal of the normal to the reflecting surface has not so far been considered.

6. MDLA AZIMUTHAL GEOMETRY

The MDLA mirror is concave in azimuth to provide a relatively wide azimuth field in which the image may be acquired and tracked to touchdown. For a mirror of width $2d$ and radius of curvature R, together with a mirror-to-source lights distance of D_L, the nominal total azimuthal coverage, γ, is given by

$$\gamma = 2[2\sin^{-1}(d/R) - \tan^{-1}(d/D_L)]\,.$$

Using the installation data given in Section 4, viz:

$2d = 5'$
$R = 10'$
$D_L = 138'$

then

$\gamma \simeq 56^\circ$.

Hence, if the source lights were on the optical axis of the mirror then the coverage would be symmetric, ± 28 degrees, about that axis.

The mirror and source lights have been installed at approximately the same distance offset ($\simeq 45$ ft) from the angle centre-line. However, as stated in Section 2, the mirror mount is set orthogonal to the axial centre-line and although some adjustment in azimuth is available there is insufficient to align the mirror optical axis parallel with the angle centre-line.

The azimuth setting of the mirror optical axis has little effect on the performance of the system other than on the field of view of the image. The most critical feature is that the image should still be visible to the pilot at the touchdown point closest to the mirror. The adjustment in azimuth is thus an installation setting and is made such that the image cut-off occurs at a point on the angle centre-line 15 ft forward of No. 5 wire (20 ft forward of the nominal hook touchdown point for No. 5 wire). When set for this condition the coverage field has been set to give the maximum coverage on the port side of the carrier for in-flight acquisition of the image (see Fig. 10).

Taking the offset distance from the angle centre-line of both the mirror and the centre of the source lights as 45 ft (see Fig. 11) then the azimuth angle, with respect to the angle centre-line,

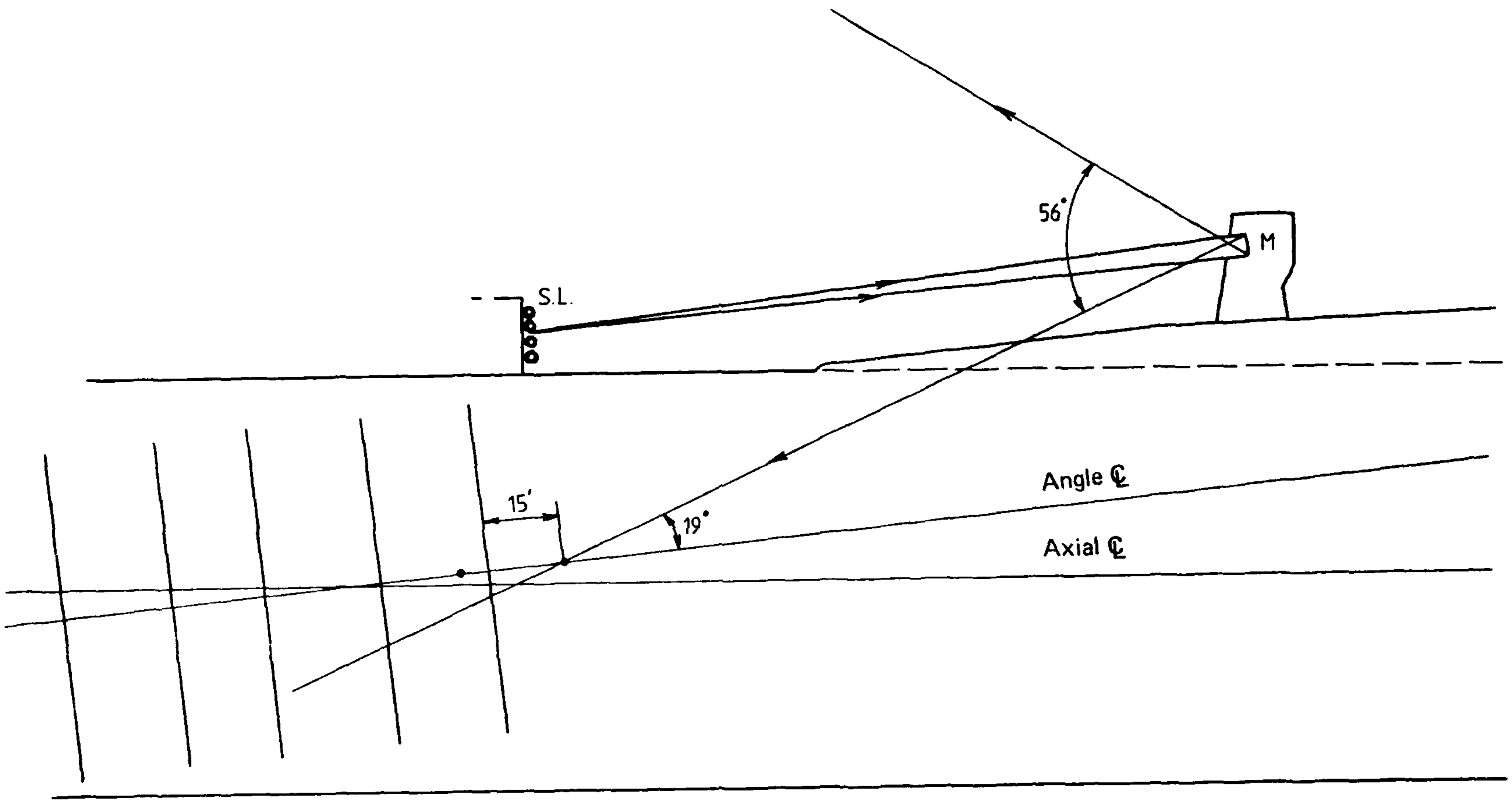


FIG. 10 MDLA AZIMUTH COVERAGE

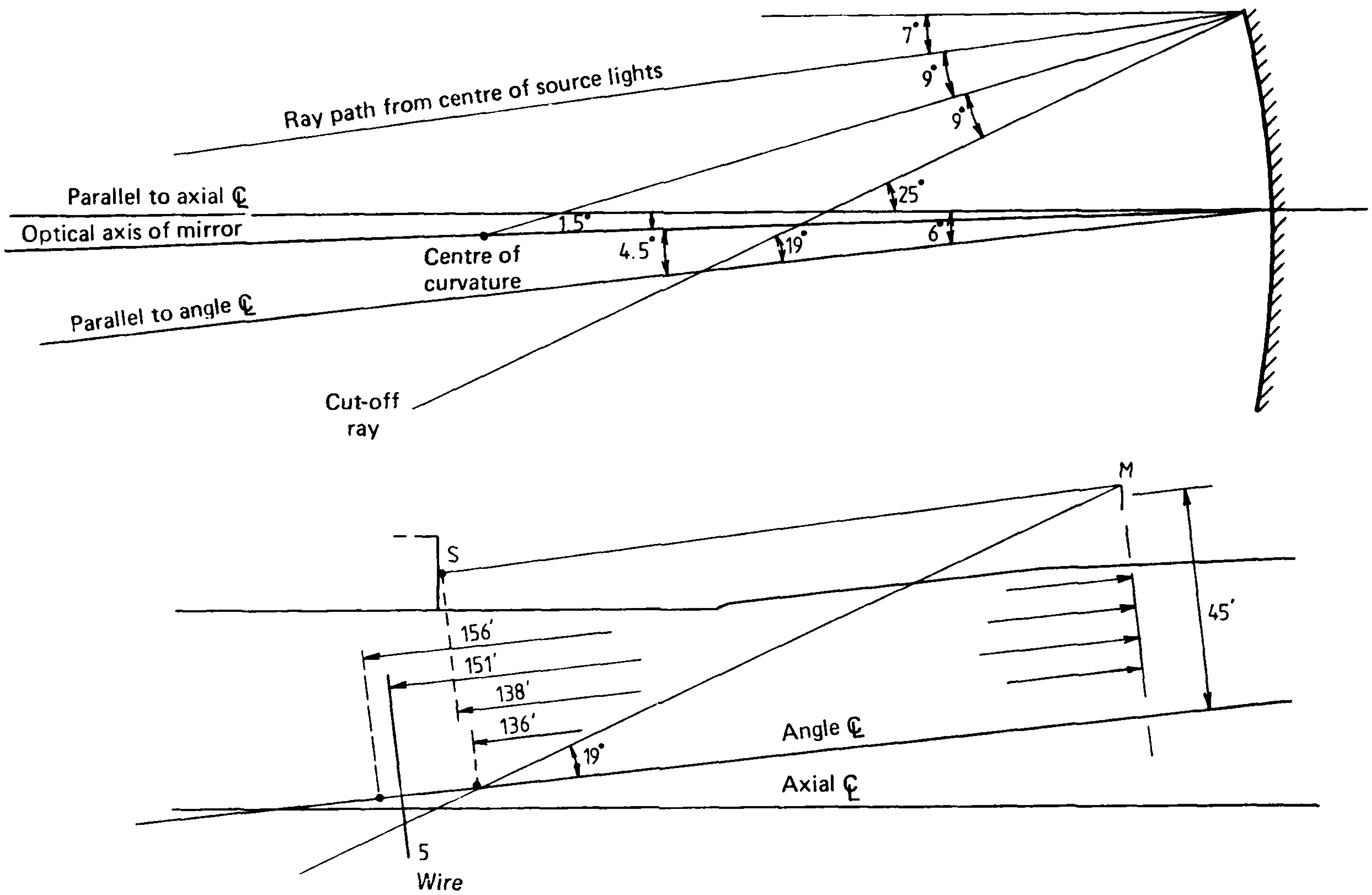


FIG. 11 CUT-OFF RAY PATH GEOMETRY

of the ray path from the far edge of the mirror to the specified cut-off point is given by

$$\tan^{-1}(45 \cdot 2{\cdot}5/136) \simeq 19^\circ .$$

To obtain that cut-off condition the optical axis of the mirror must be offset from the angle centre-line, towards the axial centre-line, by angle δ where

$$28^\circ - 2\delta \simeq 19^\circ$$
$$\delta \sim 4{\cdot}5^\circ .$$

The horizontal span of the source lights (3 × 22 in. + 10½ in.) subtends an angle of 2·6 degrees at the face of the mirror. Cut-off of the compound image of the four source lights thus occurs progressively across the same angular span, i.e. from 17·7 degrees to 20·3 degrees ($19^\circ \pm 1{\cdot}3^\circ$). This is equivalent to an azimuth adjustment range on the mirror of ±0·65 degrees. The setting is thus reasonably non-critical.

The value of 4·5 degrees obtained above for δ is consistent with the observation (Section 2) that the mirror appeared to be set at about 1½ degrees offset from the axial centre-line.

A diagram attached to Reference 2 shows the optical axis of the mirror passing 10 ft outboard of the centre of the source lights, i.e. 58 ft offset from the axial centre-line at Frame 168. This is equivalent to an offset angle of

$$\tan^{-1}(63-58)/138) \simeq 2^\circ .$$

The basis for the value of 10 ft is not known but the result is reasonably consistent with the other data given above.

The azimuth setting of the mirror determines the axis about which pitch stabilisation of the mirror occurs. The effects of ship pitch and roll are examined in a later section and the pitch stabilisation axis is taken to be the 1·5 degree value.

7. MEASUREMENT METHODS

The critical measurements are those associated with the determination of H_0, H_D and β_0. In turn, these require the specification of a "deck reference plane" or a "mean deck plane".

It is also understood that the H_S and β_S scales are not uniquely fixed within the mirror assembly but are linked to the adjustment servo gear trains. Maintenance and repair actions are thus likely either to change the values of H_0 and or β_0, or to require their careful resetting.

The G.I.D. measurement techniques are based on the use of gravitationally referenced devices (clinometers, theodolites, etc.) so that the various measurements require correction for residual deck plane pitch and roll. Also if the deck is not absolutely steady there are changes with time that make corrections more difficult to establish.

A method for making direct measurements of H_0 and β_0, via the *in situ* H_S and β_S scales, is described below which overcomes these problems and which could, in fact, be used at sea in reasonably smooth conditions. The technique was checked as feasible when HMAS *Melbourne* was berthed in Melbourne, Victoria, in September 1977 and was used successfully by the author for obtaining measurements whilst the ship was in dry dock at Garden Island in December 1977.

The method involves creating a measurement plane, displaced from, but parallel to, the "deck reference plane", and then aligning the mirror to this plane in both height and elevation. Choosing the displacement to be around 30 to 36 in. sets the displaced plane at the mid-working range of height settings of the mirror. Height scale readings can then be obtained directly.

The displaced plane is created by setting up three spacer rods, of equal length, near vertical and standing on the flight deck at three suitably chosen reference points. An optical telescope with two-axis tilt adjustment and vertical height adjustment is set up in height and tilt to sweep its sightline azimuthally in the displaced plane.

With the telescopic head thus set the mirror can be raised or lowered to bring the lateral centre-line of the mirror (as defined by the datum lights) into coincidence with the displaced plane. The setting, H_S, on the vertical height scale, together with the known length of the spacer rods, determines $H_1 - H_0$. Similarly a surveyor's rule set up at the source lights and read through the telescope determines H_D, and thence H_0.

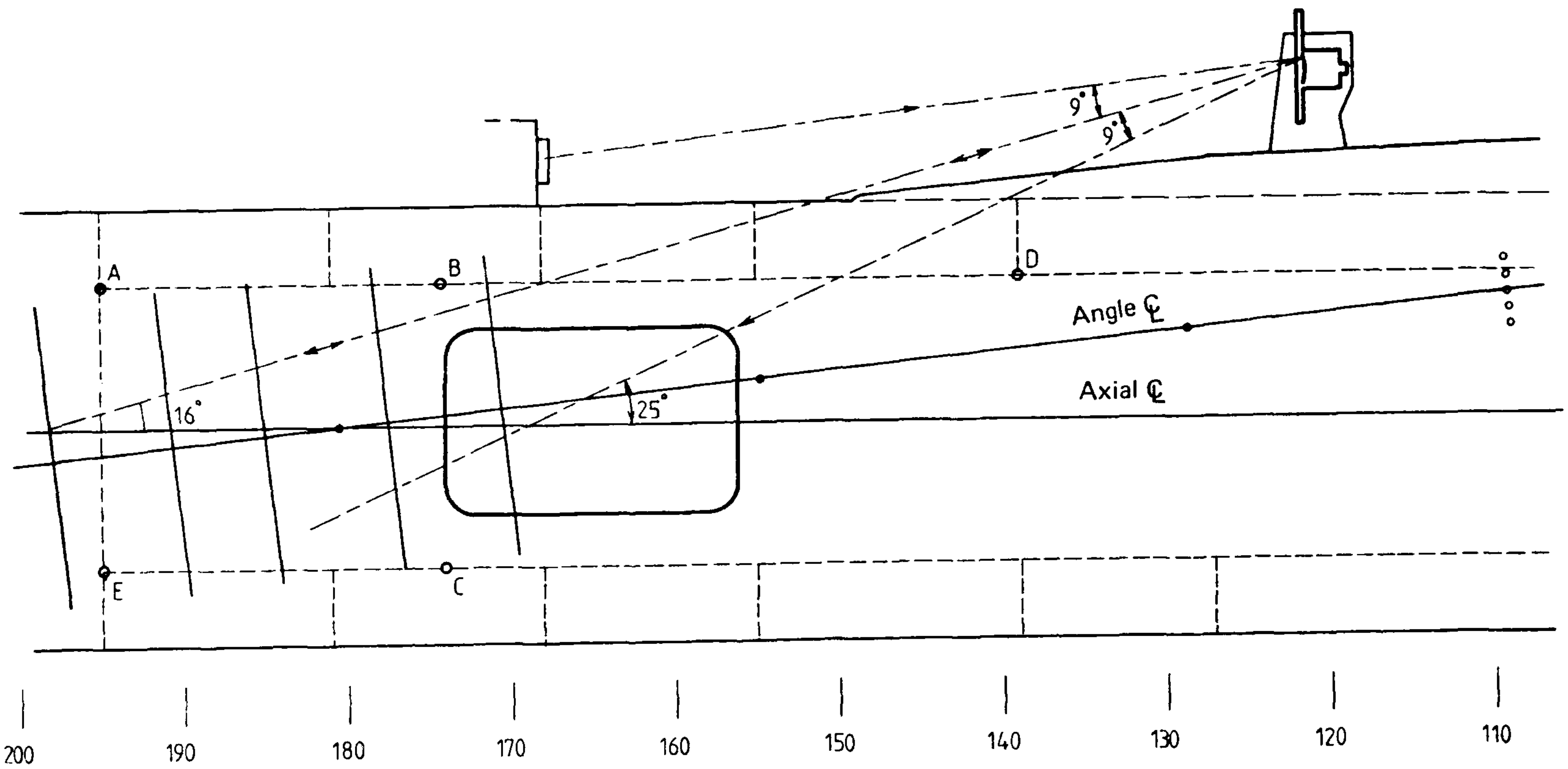


FIG. 12 DECK REFERENCE POINTS

With the mirror set at that vertical height the elevation angle can be adjusted, without stabilisation inputs, until the normal to the mirror surface is also coincident with the displaced plane. This is most easily accomplished by using a light source mounted beside, and at the same height as, the telescope. An intermittently flashing light facilitates identification of the reflected ray. When the mirror is adjusted in elevation so that the image of the flashing light is seen to be on the line of the datum lights then the forward and reflected rays (and thus the normal to the mirror surface) lie in the displaced plane. In this condition the mirror elevation is identically zero with respect to the deck reference plane, despite any quiescent ship pitch or roll that might be present. That condition is the datum condition from which all stabilisation corrections should be made. Although nominally off-scale in this condition the angle setting can be determined from the graduated scale on the drive shaft. The value of β_0 is thus directly determinable.

The spacer rods used by the author were each arranged to have a screw-on head shaped to provide a longitudinal marker rod (½ in. diameter) carrying a transverse disc (¼ in. thick) that would appear as a cross for sighting purposes when viewed horizontally. The base of the rod was cone shaped and the length from tip of cone to centre of transverse disc was machined to 36 in. $\pm 0{\cdot}010$ in. Each rod was supported in a tripod based tube such that the conical tip rested freely on the flight deck at a selected reference point. The tripod feet were adjusted to set the tube near vertical. As used a plumb line down the centre of the tube, before installing the rod, was used to obtain greatest accuracy. Considerable tolerance can, however, be allowed in setting the rods "vertical"; resulting errors in height being of the form $(1 - \cos \epsilon)$ giving less than $\frac{1}{16}$ in. error in 36 in. for 3 degrees off the vertical.

The choice of the three deck reference points is worthy of some discussion. The reference points used by G.I.D. for periodic measurement of flight deck distortion are nominally 26 ft offset from the axial centre-line, on the port side at Frames 195 and 174 and on the starboard side at Frame 174 (points A, B and C in Fig. 12). These points were chosen where the deck is stiffened by vertical support structure below the deck. Frame 174 is conveniently identified as the aft edge of the lift aperture. Although well placed for measurements in the region of the wires, they are about 150–200 ft from the mirror with a longitudinal base-line AB of only 63 ft. Extrapolation to the mirror position is a potential source of error. A longer base-line would result from using point A with point D at Frame 139. Point D is chosen as the point closest to the mirror lying above the hangar wall at which there is also lateral stiffening from a compartment wall.

To use the telescope method for elevation calibration the telescope itself must be set up at a site from which it is possible for the image of the flashing light to be visible in the mirror. The limiting ray path for this purpose is shown in Figure 12. The allowable sector for siting the telescope lies port of a line from the mirror passing approximately through the intersection of No. 1 wire with the axial centre-line, and also passing approximately through the central light of the aft Bedford Lights near Frame 209.

In practice, the further port that the telescope can be sited the better for calibration purposes, because the point of reflection on the mirror at which the normal is being assessed is then closer to the centre of the mirror, and thus closer to the portion of the mirror that is used by a pilot for most of his approach. Point A is therefore the optimum reference point next to which the telescope should be sited.

Having chosen points A and D on the port side the third reference point must be chosen on the starboard side to give a lateral base-line. Point E in Figure 12 at Frame 195 provides for a 90 degree swing on the telescope for alignment purposes and is probably optimum in that the below-deck stiffening is both longitudinal and lateral. Point C provides a 40 degree swing on the telescope and thus could be slightly more convenient for a telescope having a tilt bed with three-point adjustment.

8. 1977 MEASUREMENTS

In December 1977, whilst HMAS *Melbourne* was in dry dock at Garden Island, recalibration of the MDLA, following a maintenance overhaul, was undertaken by G.I.D. staff using theodolite and clinometer methods. The opportunity was made available for the author to make independent measurements using the displaced plane method, described in Section 7, as a cross-check.

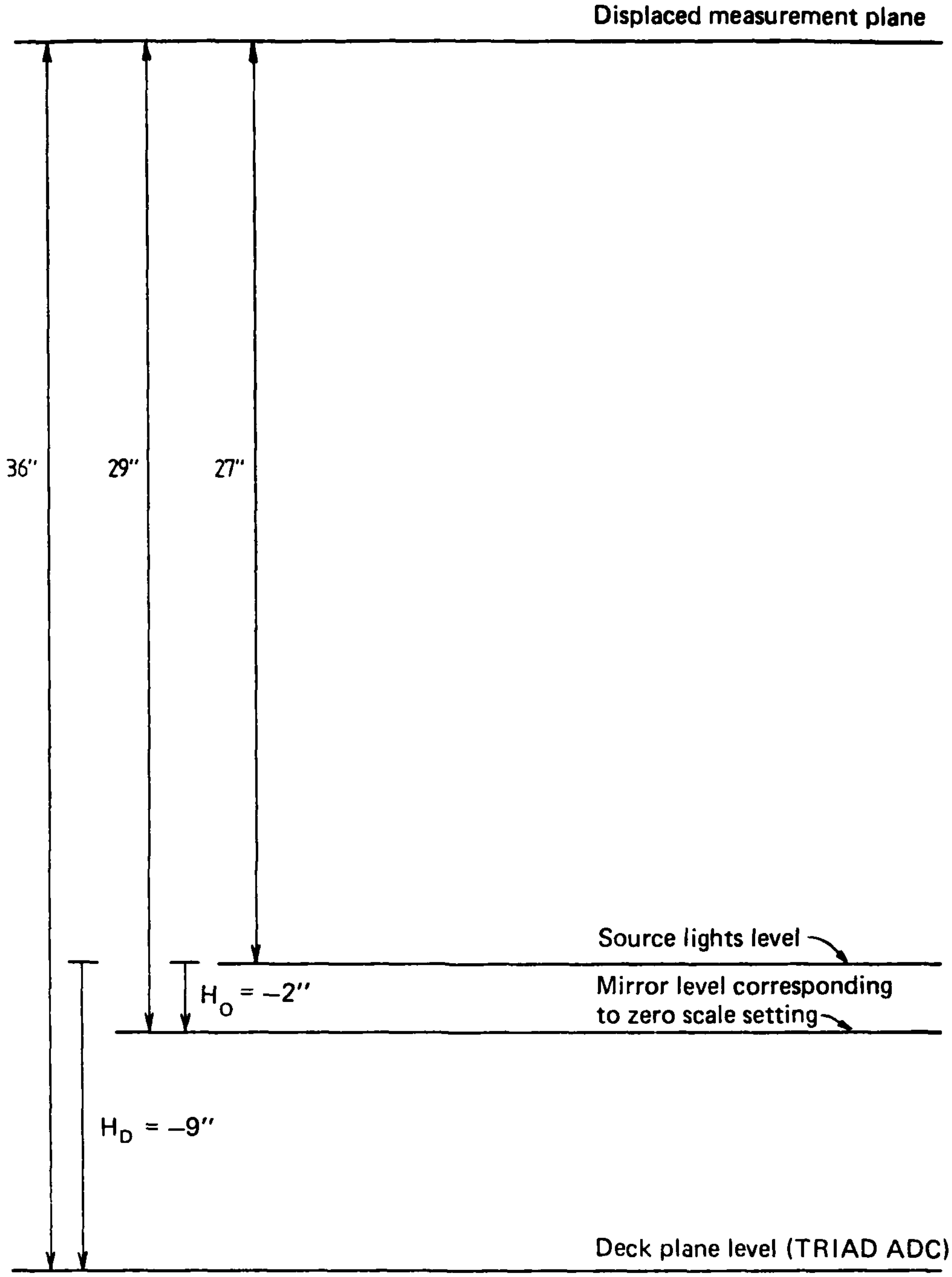


FIG. 13 DIFFERENTIAL MEASUREMENTS, DEC. 1977.

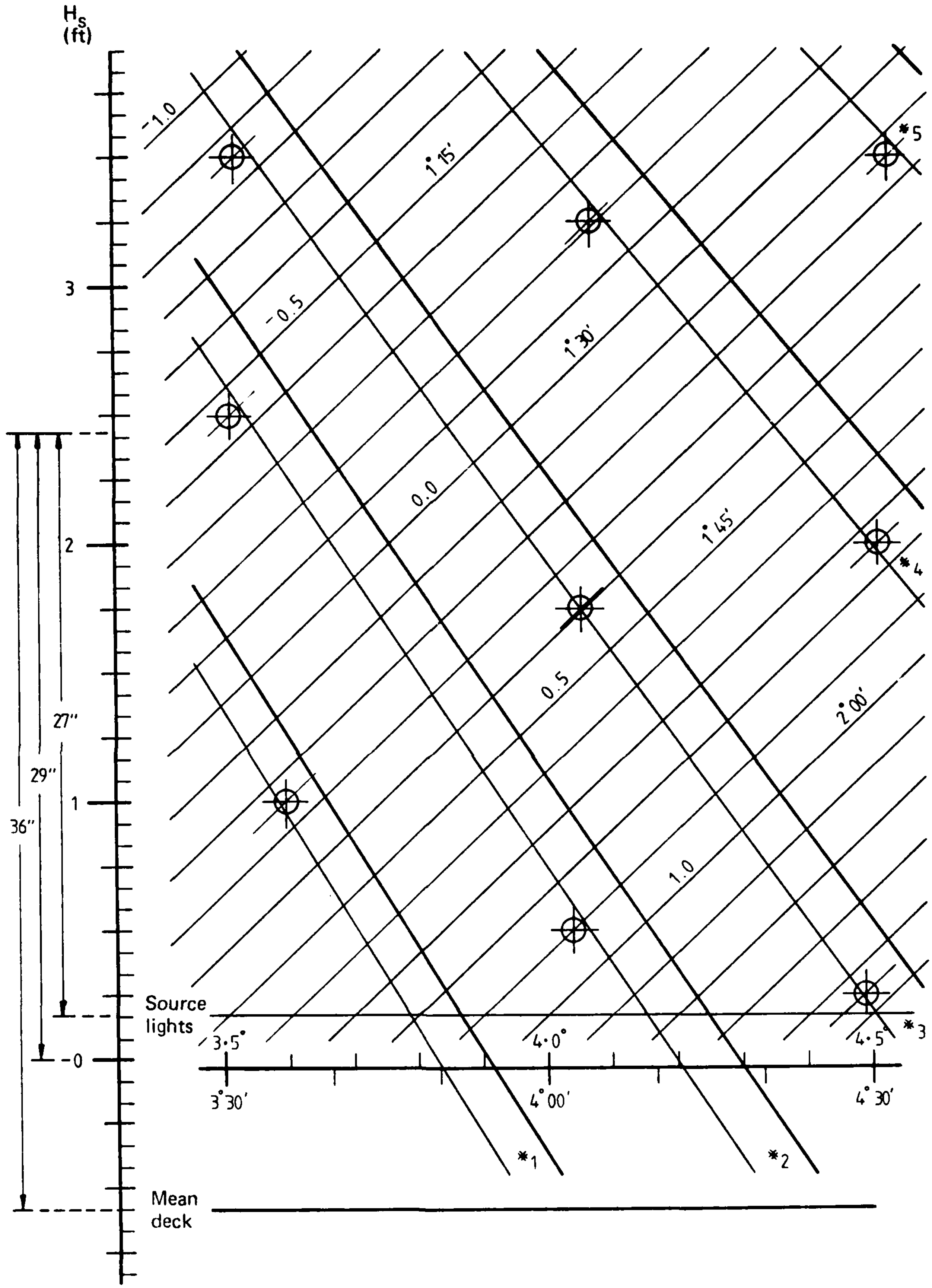


FIG. 14 S – 2E CONDITIONS, 1977 DATA

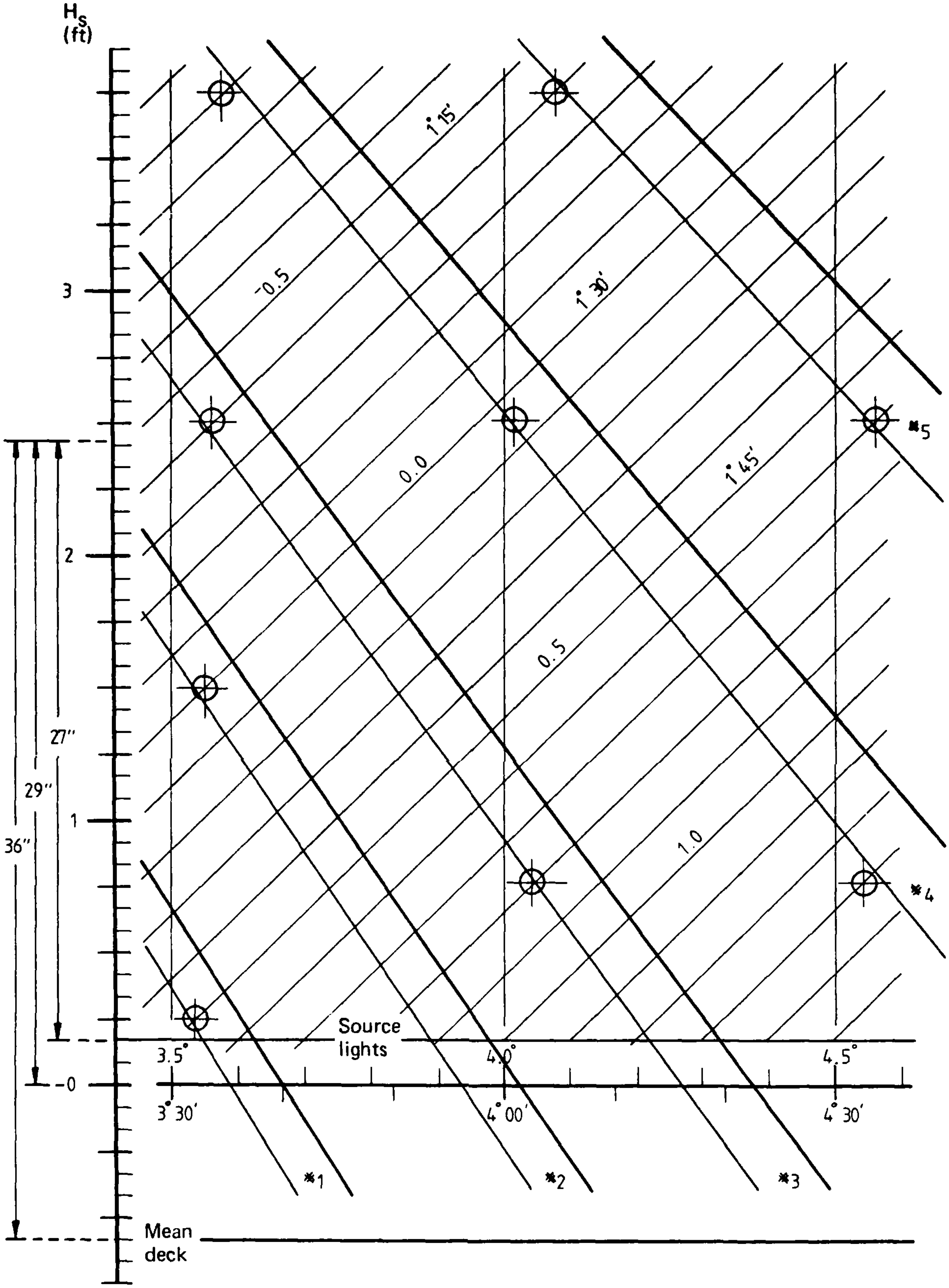


FIG. 15 A – 4G CONDITIONS, 1977 DATA

At that time points A, B, C and D (Fig. 12) had been located and identified by G.I.D. staff. The triad ABC was used by G.I.D. for measurement of deck distortions in the region of the wires and also to check the level at point D. The vertical deviation of point D from the reference plane defined by triad ABC was reputedly less than 1 in. The triad ADC was used by the author for measurements on the mirror.

The vertical measurements obtained were (see Fig. 13)—

(i) Rod length: 36 in.
Displaced measurement plane thus 36 in. above the plane defined by triad ADC.

(ii) Mirror height scale reading: 29 in.
Taken with the mirror set such that its mid-point (defined by the line of the Datum Lights) lay in the displaced plane. Hence the zero of the height scale is equivalent to a mirror setting such that its mid-point is 7 in. above the plane defined by the triad ADC.

(iii) Source lights rule reading: 27 in.
Taken with the surveyor's rule set vertically with its base on the lateral centre-line of the source lights. Hence the source lights are located 5 in. above the plane defined by the triad ADC.

The elevation calibration was completed with a flashing light source in the manner previously described. The elevation scale and gear train had not at that time been set up; therefore,no scale reading was obtained. The graduated scale on the drive shaft, however, was close to minus 3 degrees (of θ) and was adjusted to that setting. The implicit setting on that scale was thus minus 1 degree 30 minutes in β_S corresponding to a β_0 of plus 1 degree 30 minutes.

Using the values obtained above, together with a mirror-to-source light distance of 139 ft (the value recorded by G.I.D.), plots for the S-2E and A-4G are as shown in Figures 14 and 15 respectively. The data used were:

$H_0 = -2''$
$H_D = -9''$
$H_V = 16{\cdot}5'$, S-2E
$\quad\quad 15{\cdot}5'$, A-4G
$D_L = 139'$

$D_W =$	233′	$D_T = 238'$	No. 1 wire
	212′	217′	2
	195′	200′	3
	172′	177′	4
	151′	156′	5.

No corrections for deck distortions are included. Also shown on the plots are suitable settings for H_S and β_S based on the data used. *It should be noted particularly that the settings indicated are not necessarily consistent with those promulgated from Navy Office for current use on the MDLA.* Changes in the equivalent values of the zero settings on the scales may occur for a variety of reasons. In addition the promulgated settings may be based on consideration of other relevant data.

In the category of "other relevant data" is the set of clinometer measurements made on the lateral centre-line of the mirror face. These were intended to check the quality of the mirror surface. It is understood that a progressive change in the elevation of the normal across the mirror face was detected. The magnitude of the change from the centre of the mirror to the port edge of the mirror was apparently 7 minutes of arc. This is sufficient to give rise to ¦ degree difference between the glide slope as inferred from pole check and the glide slope as seen by a pilot well aft of the ship.

9. MDLA SPATIAL COVERAGE

In this section the spatial coverage of the MDLA system is developed with particular reference to the effects of ship pitch and roll. The optically propagated glide slope is stabilised in pitch by correcting the elevation angle of the mirror by an angle equal to half the ship pitch angle. There is no equivalent compensation for ship roll.

The mathematical equations used to calculate the coverage diagrams are given in detail in Appendix A. The technique used is that of ray path calculation based on a point source (taken to be the centre of the source lights) and a nominated point of reflection on the face of the mirror. An observer's eye located on the path of the reflected ray would thus observe the image of the source lights to be centred at the nominated point of reflection. Sweeping the point of reflection parametrically across the face of the mirror, laterally and vertically, generates the spatial coverage for a particular combination of mirror settings and ship pitch and roll.

The coverage diagrams are calculated for only one set of mirror settings, viz those appropriate to a "mid-range" set of conditions. These are taken, for convenience, to be

$$H_S = 1\cdot5'$$
$$\theta = 4^\circ$$

corresponding to

$$\beta_M = 1^\circ 43\cdot5'$$
$$\text{Angle setting} = +0\cdot45^\circ$$
$$\beta_S = +0\cdot225^\circ\ (+13\cdot5')$$

and equivalent to an approach for No. 3 wire for an aircraft with hook–eye height of close to 16 ft.

The exact conditions for β_S and H_Y are given by

$$\beta_M = \beta_S + \beta_0 = \tfrac{1}{2}[\theta - \tan^{-1}(H_M/D_L)]$$
$$H_M = H_S - H_0 = H_Y + H_D - (D_W + 5)\tan\theta$$

with

$$\beta_0 = 1^\circ 30'$$
$$\theta = 4$$
$$H_S = 18''$$
$$H_0 = -2''$$
$$H_M = H_S + H_0 = 16''$$
$$D_L = 139'$$
$$H_D = -9''$$
$$D_W = 195'$$

giving

$$\beta_S = -0\cdot2252^\circ\ (-13\cdot51')$$
$$H_Y = 16\cdot069'\ (16'\ 0\cdot82'').$$

In order to compute correctly the effects of ship pitch and roll the relevant axes for pitch and roll motion must be defined. That data was obtained from RAN sources and is given below. In the absence of any evidence to the contrary the assumption has been made that these two axes intersect, thus defining a "centre of pitch and roll".

In fact the axes about which ship pitch and roll motions occur are not unique. They depend firstly on the draught or displacement, and secondly on the attitude (instantaneous values of pitch and roll) of the ship. Information provided by the RAN Directorate of Naval Ship Design is given below (see also Fig. 16):

(i) for small motions (up to 5 degrees of pitch and roll) the axes of pitch and roll may be taken as fixed with respect to the ship's frame and intersecting one another;

(ii) the lateral axis of ship pitch motion lies 26 ft aft of "midships", defined by Frame 105, and thus lies 24 ft forward of the mirror position;

(iii) the longitudinal axis of roll motion may be assumed to pass through the metacentre and for a draught of 25 ft to lie approximately 6 ft above the water waterline;

(iv) for a draught of 25 ft the flight deck is 37½ ft above the waterline.

The locations, in plan, of the mirror, source light and angle centre-line, assumed for the purpose of calculating the coverage diagrams are as defined in Figure 17 and based on the following:

(*a*) the angle between the angle centre-line and the axial centre-line is 5·85 degrees;

(*b*) the angle centre-line intersects the axial centre-line at a point (nominally at Frame 179) on the axial centre-line 222 ft aft of midships (nominally at Frame 105);

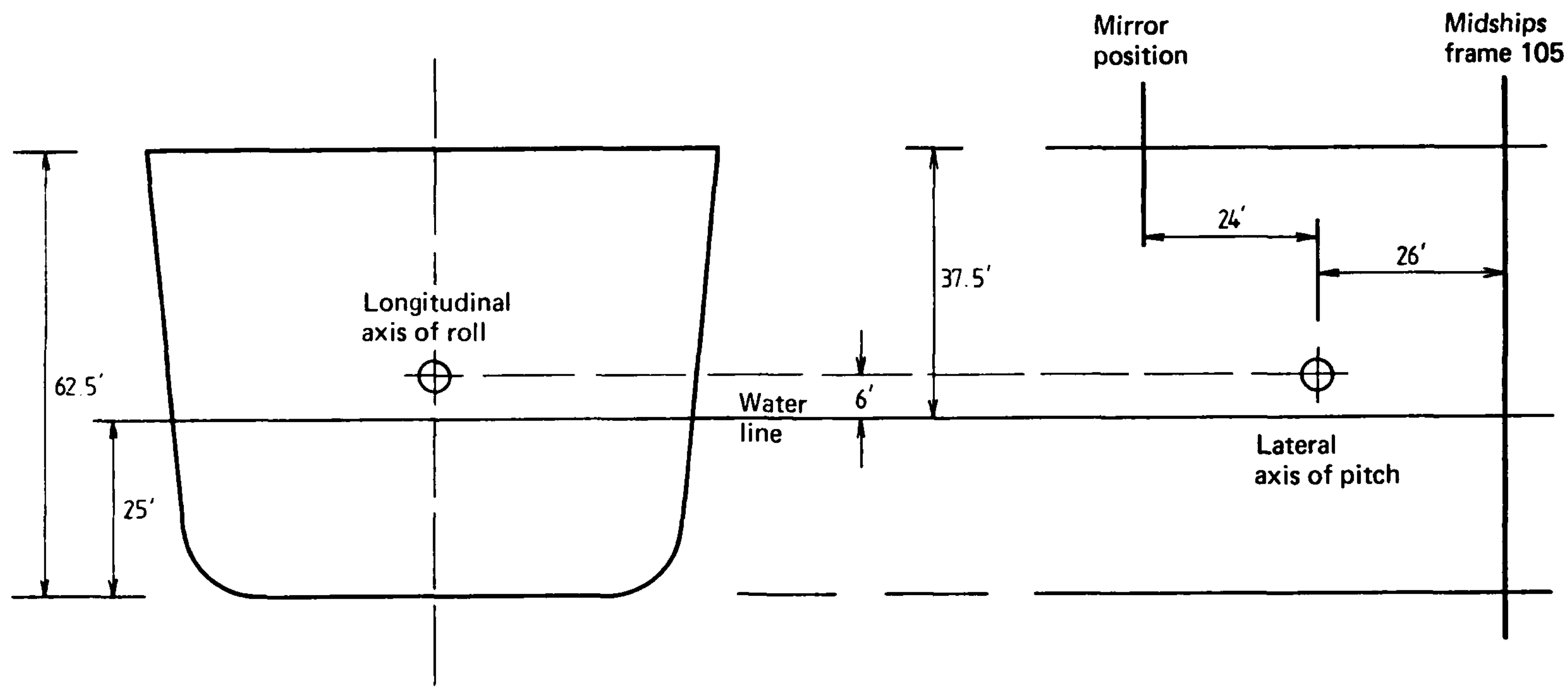


FIG. 16 'CENTRE' OF PITCH AND ROLL

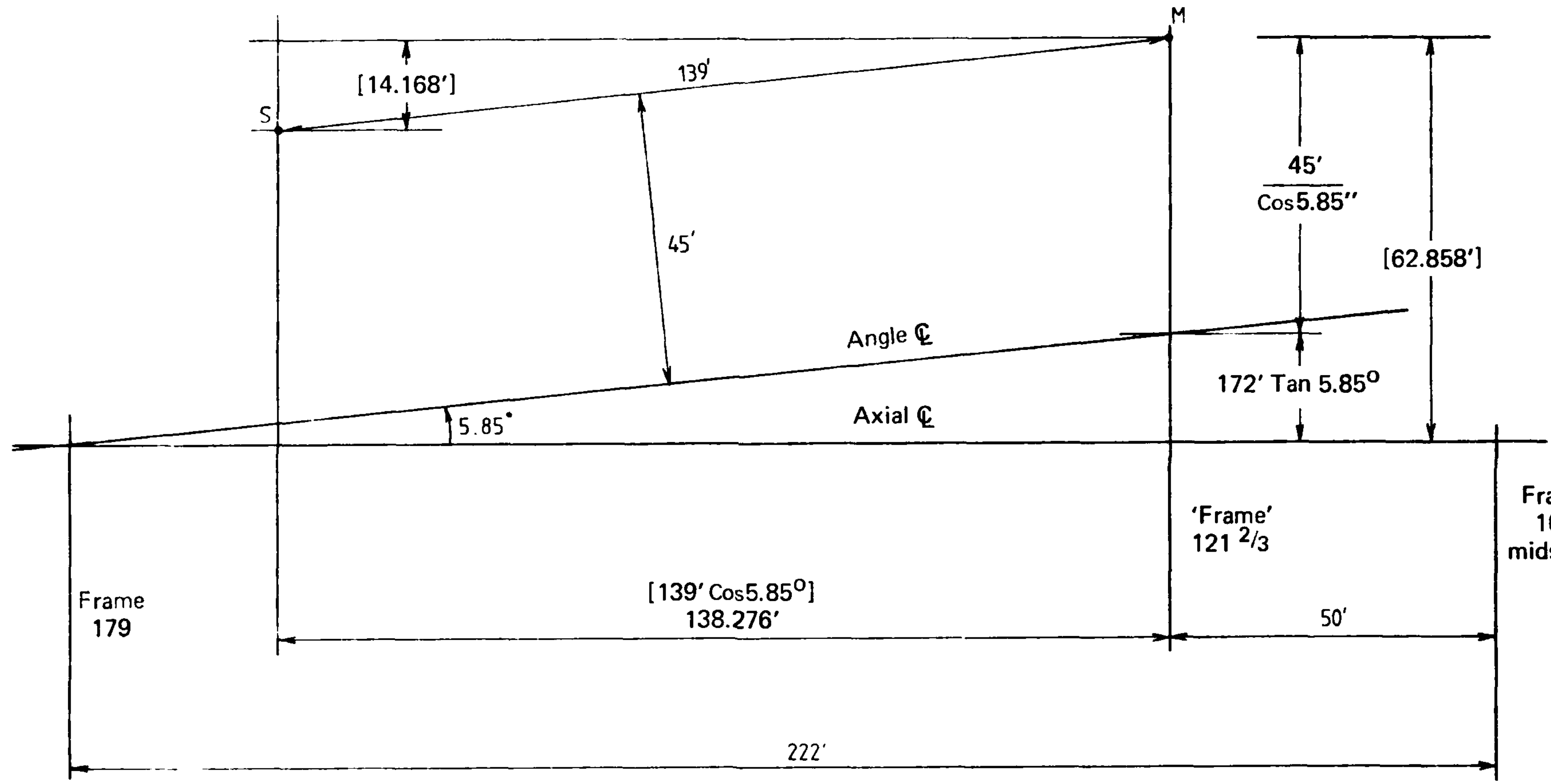


FIG. 17 MIRROR, SOURCE AND ANGLE CENTRE-LINE LOCATIONS ASSUMED FOR SPATIAL COVERAGE CALCULATIONS

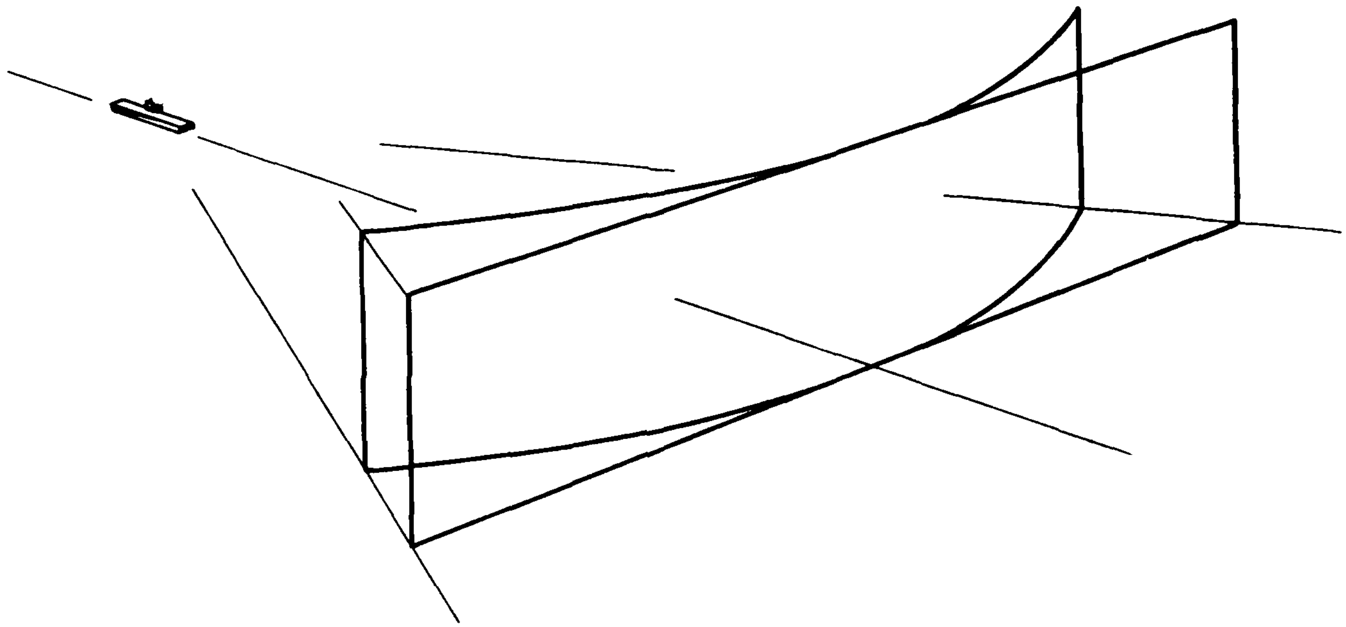


FIG. 18 PLANE AND CYLINDRICAL SURFACES OF INTERSECTION FOR REPRESENTATION OF COVERAGE DIAGRAMS

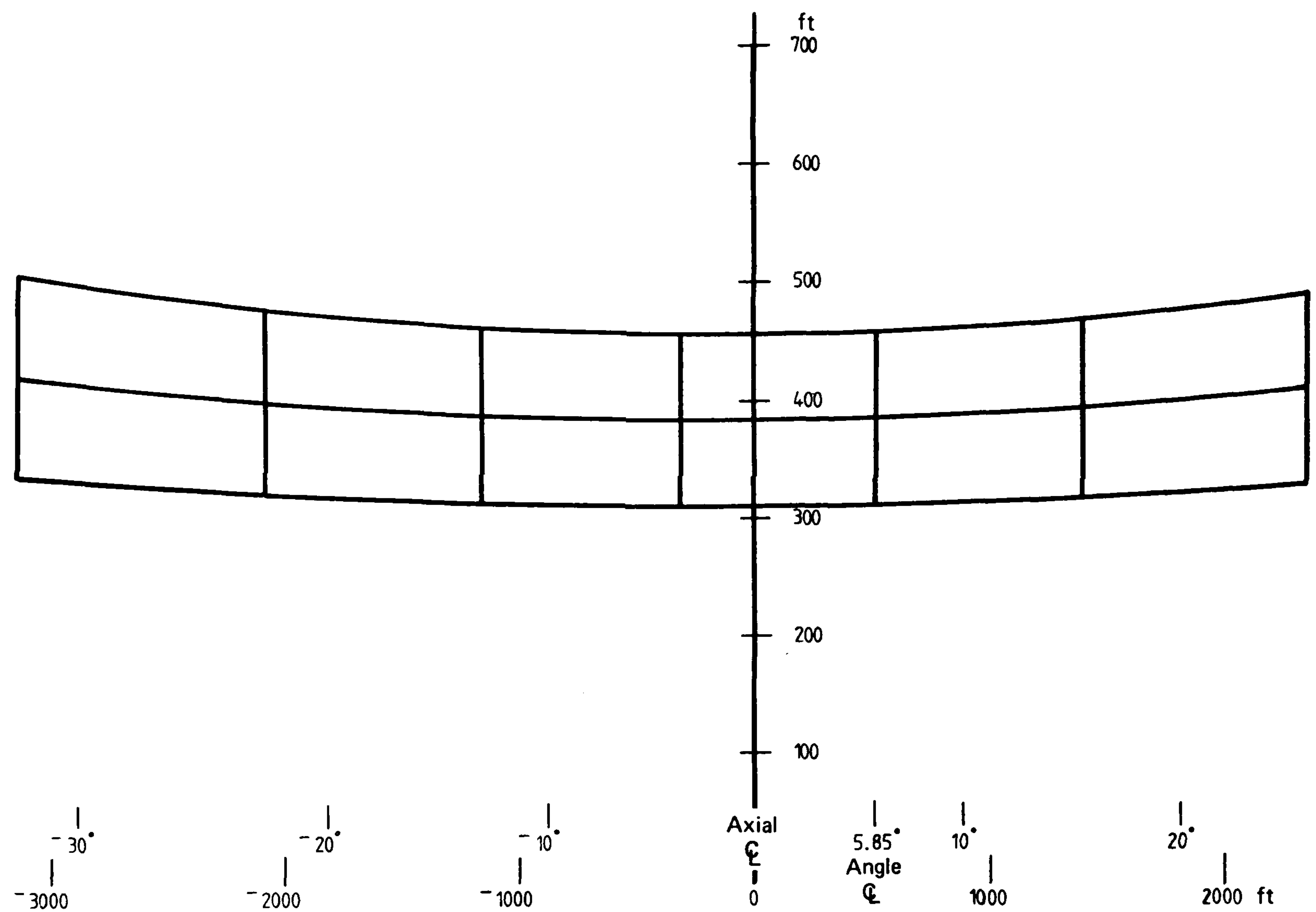


FIG. 19 MDLA COVERAGE – 5000 FEET AFT, PLANE SURFACE OF REPRESENTATION

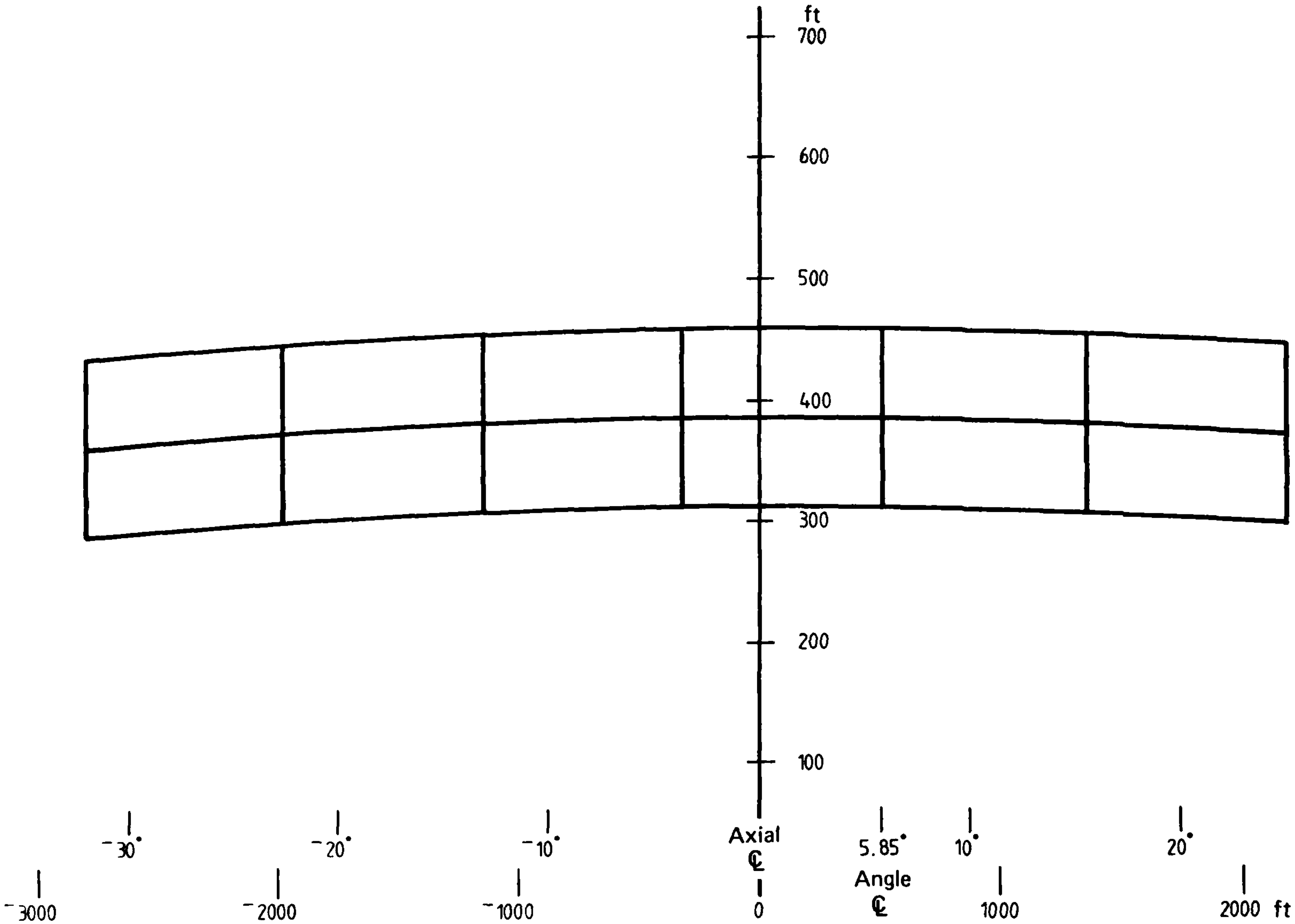


FIG. 20 MDLA COVERAGE – 5000 FEET RADIUS, CYLINDRICAL SURFACE OF REPRESENTATION

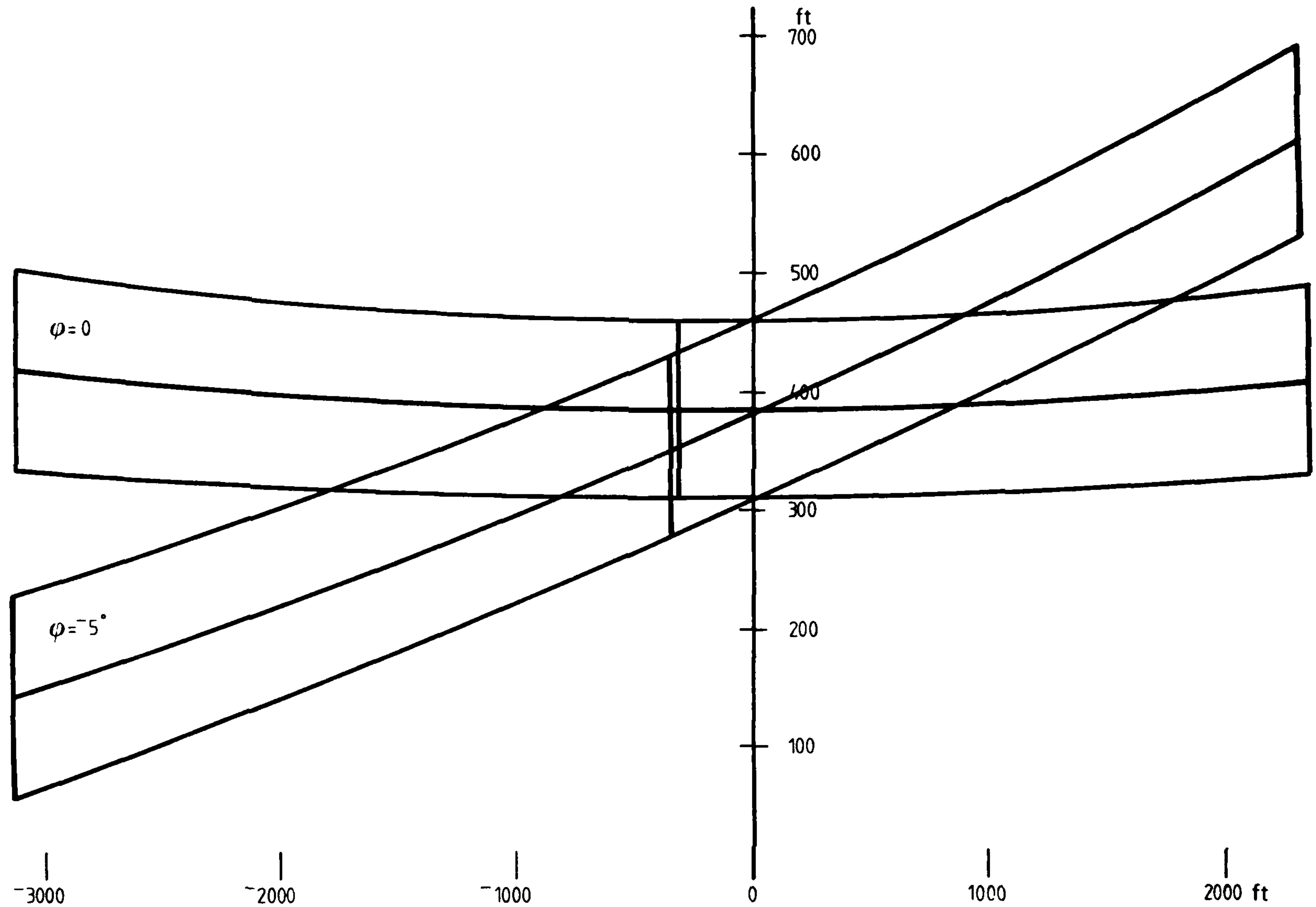


FIG. 21 MDLA COVERAGE – EFFECT OF SHIP ROLL, PLANE SURFACE OF REPRESENTATION (5000 FEET)

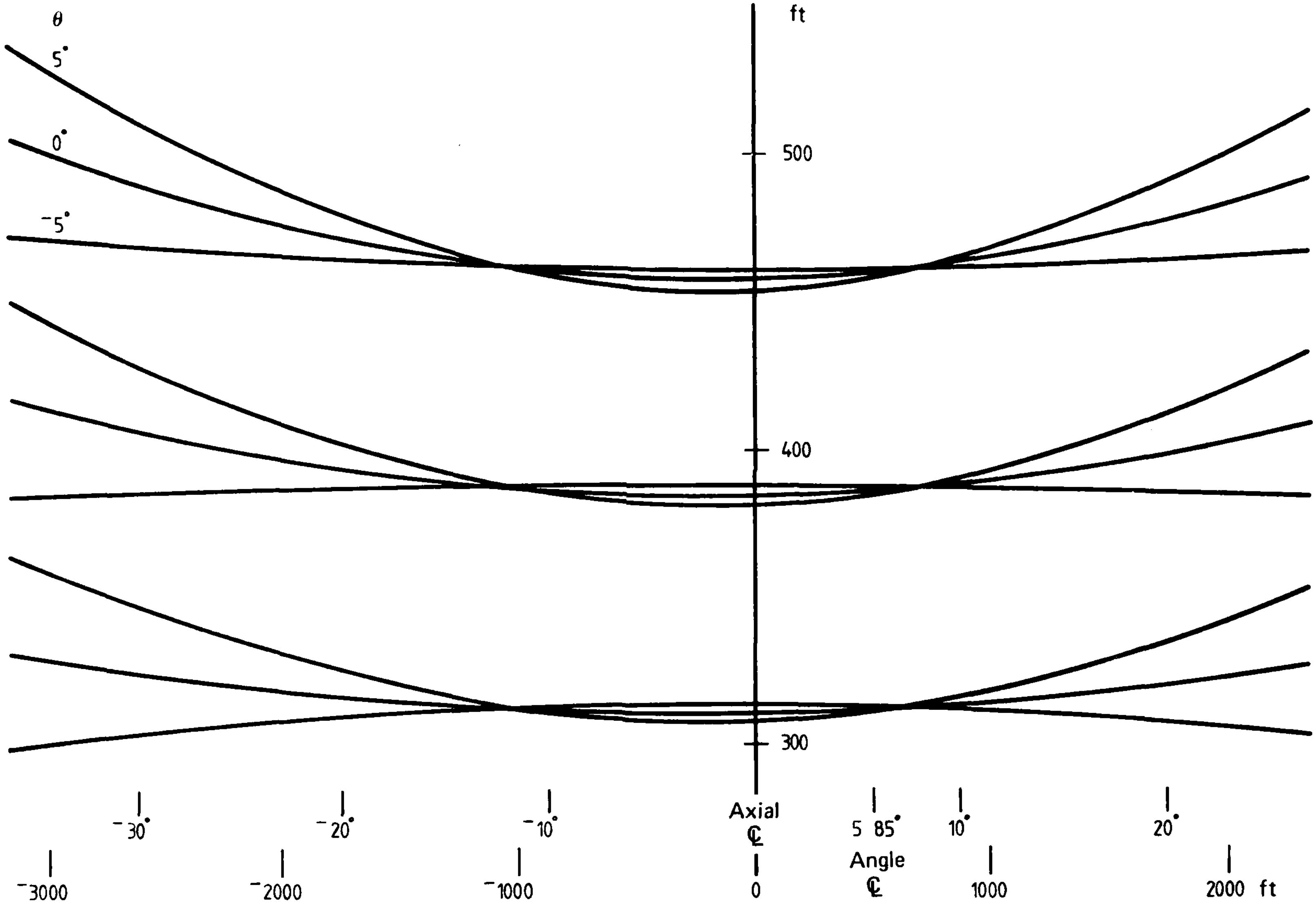


FIG. 22 MDLA COVERAGE – EFFECT OF SHIP PITCH, PLANE SURFACE OF REPRESENTATION (5000 FEET)

(*c*) the centres of the mirror and source lights lie on a line displaced 45 ft to port of the angle centre-line;

(*d*) the longitudinal position of the mirror (nominally "Frame" 121⅜) is 50 ft aft of midships;

(*e*) the distance from mirror to source lights is 139 ft.

This method of specifying the positions of the mirror and source lights was chosen in order that the mathematical procedure used for calculating the coverage diagrams could be adapted to a form that could provide a cross-check on the plots of Figures 14 and 15, and also to one from which the effect of the 45 ft displacement could be calculated.

For the coverage diagrams to be meaningful in terms of an aircraft making initial acquisition of the mirror image, the diagrams are presented with reference to an "Earth" axis system with origin at the sea surface and moving with the ship.

The computation procedure commences with a ship-oriented axis system with origin at the centre of the mirror and with the known co-ordinates, within that system, of the centre of the source lights. The axis system is then, by translations and rotations, aligned with a system having its longitudinal axis coinciding with the normal to the mirror surface at the nominated point of reflection. The reflected ray is easily identified in this system by change of sign of the y and z co-ordinates of the source lights. This point on the reflected ray, together with the point of reflection, identifies the reflected ray. The two points identifying the ray are then tracked through axis rotations and translations into the "Earth" axis system.

Other points on the reflected ray can be found by extrapolation along the ray path to the intersection with any required surface of representation. Two useful surfaces for depicting the coverage are:

(*a*) a vertical plane surface at a fixed distance aft of the ship;

(*b*) a vertical cylindrical surface at fixed radial distance from the ship.

In Figure 18 a pair of such surfaces are depicted representing surfaces at 5000 ft aft and 5000 ft radius from the ship.

The coverage diagrams, plotted on those surfaces, are shown in Figures 19–23. Figures 19 and 20 present the nominal coverage, for zero ship pitch and roll. The upper and lower loci represent the conditions for which the observed image of the source lights would be seen at the top and bottom edges of the MDLA mirror. Similarly the outer loci represent conditions for which the image would be seen at the lateral edges of the mirror, but with reversal of direction: *that is* at the left-hand edge of the coverage, the image is seen to the right-hand edge of the mirror and vice versa.

In Figure 21 the coverage at 5 degrees of ship roll is compared with the nominal. The absence of stabilisation is such that with significant ship roll motion there is likely to be difficulty in "acquiring" the image. For the conditions depicted, appropriate to an aircraft flying at 400 ft above sea level, on "base leg" at 5000 ft aft of the carrier, with ship roll motion of ± 5 degrees peak, the image will disappear off the top and bottom of the mirror for lateral offsets (from directly aft) of greater than about 1000 ft.

In Figures 22 and 23 the effect of ship pitch and pitch stabilisation are shown. The minor deviations from perfect corrections are due to the cylindrically curved nature of the mirror required for large azimuth coverage. It should be noted that this analysis does not take into account the dynamic characteristics of the stabilisation servo. Dynamic lags in the servo would give rise to further errors in corrections for ship pitching motion.

10. LATERAL OFFSET

Theoretical mirror settings are derived from equations appropriate to reflections within a central vertical plane (Section 3). In practice the mirror and source lights are laterally offset from the angle centre-line by 45 ft. The effect of that offset is that for an aircraft making an approach on the angle centre-line the image in the mirror is seen from a progressively increasing azimuth angle, with the image moving towards the side edge of the mirror.

It can be seen from Figure 20 that the effective glide slope as displayed by the image decreases with increasing azimuth angle. This arises from the geometry of the cylindrically curved mirror,

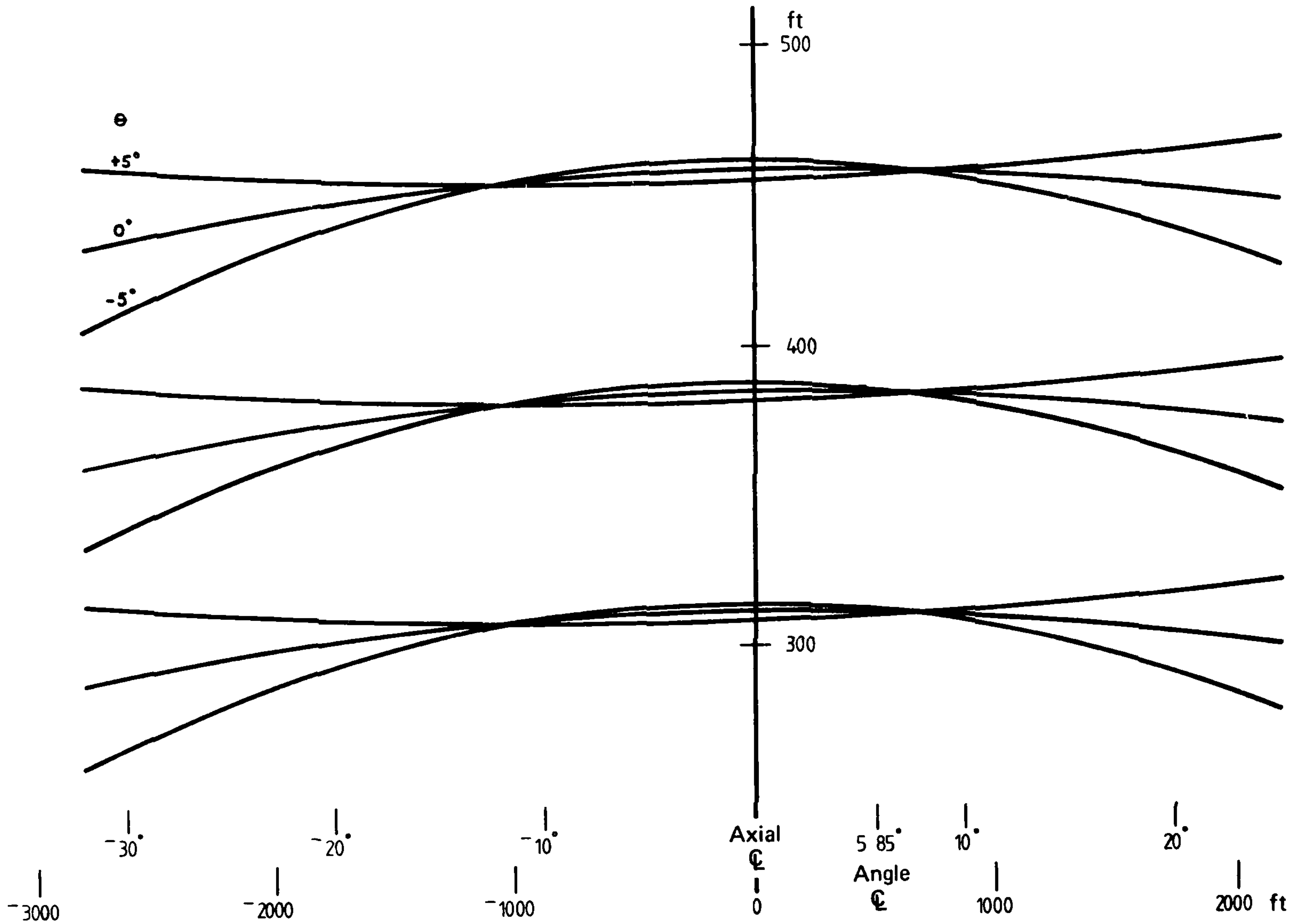
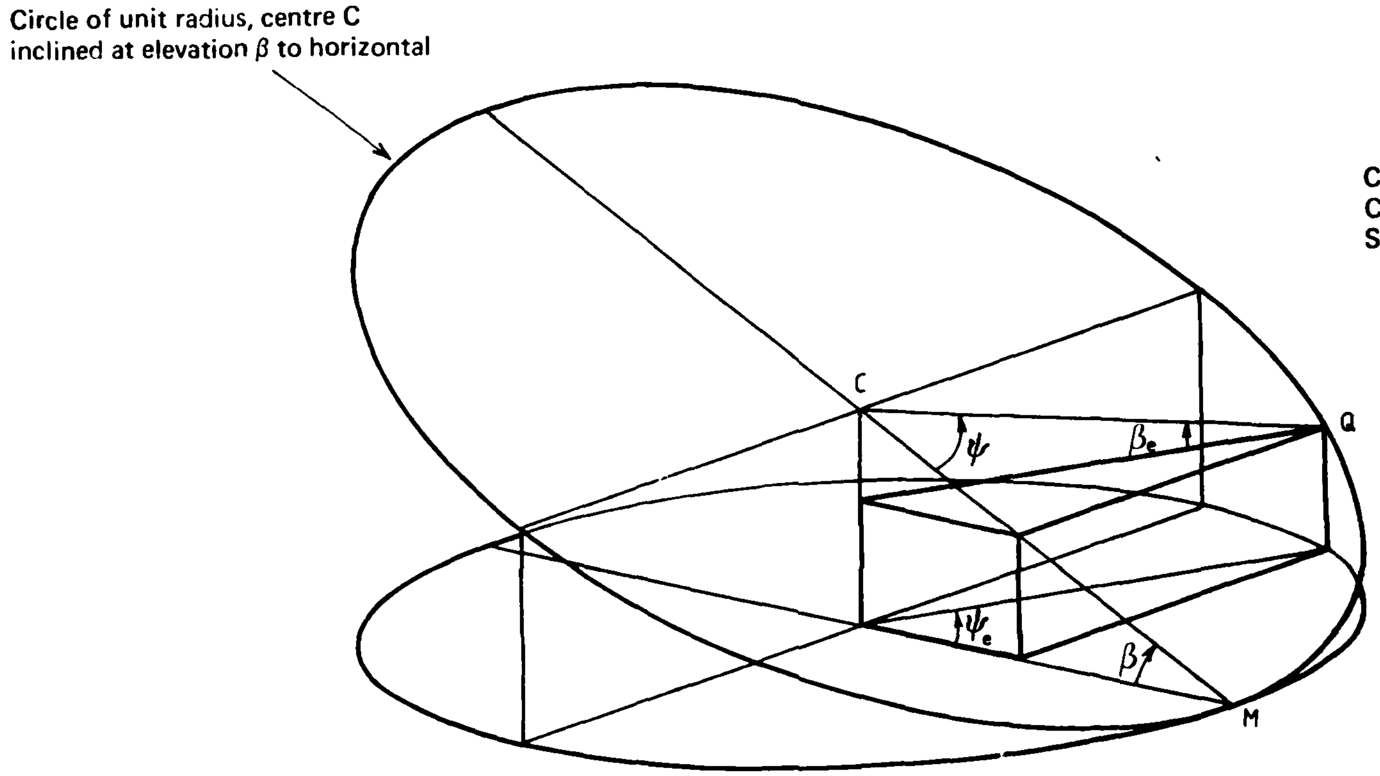


FIG. 23 *MDLA COVERAGE – EFFECT OF SHIP PITCH, CYLINDRICAL SURFACE OF REPRESENTATION (5000 FT)*



$$\begin{aligned} \cos\psi \sin\beta &= \sin\beta_e \\ \cos\psi \cos\beta &= \cos\beta_e \cos\psi_e \\ \sin\psi &= \cos\beta \sin\psi_e \end{aligned}$$

FIG. 24 RELATIONSHIPS BETWEEN ACTUAL (β, ψ) AND EFFECTIVE (β_e, ψ_e) ANGLES

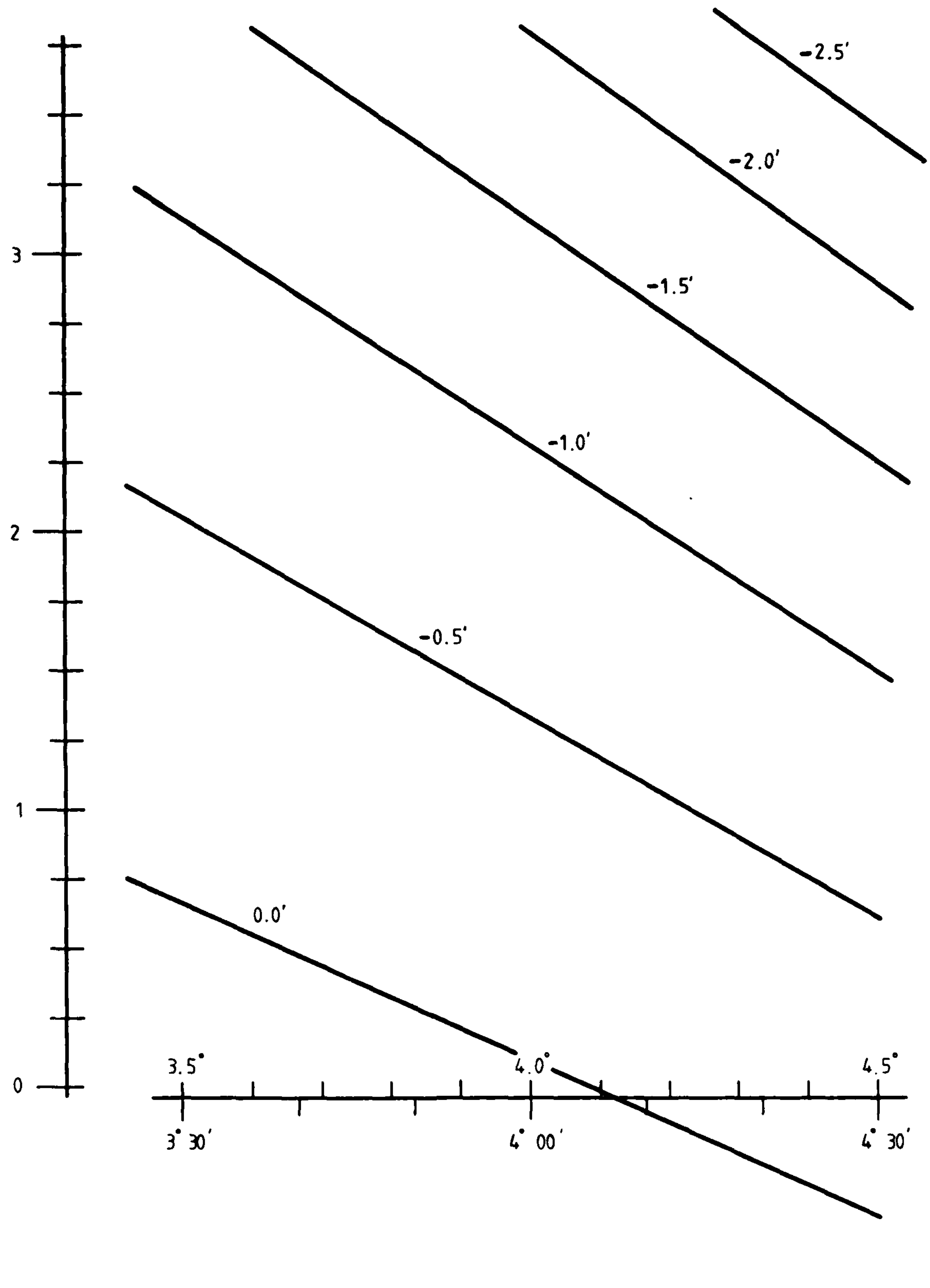


FIG. 25 ELEVATION CORRECTIONS REQUIRED FOR CONSISTENCY WITH POLE CHECKS, S – 2E CONDITIONS.

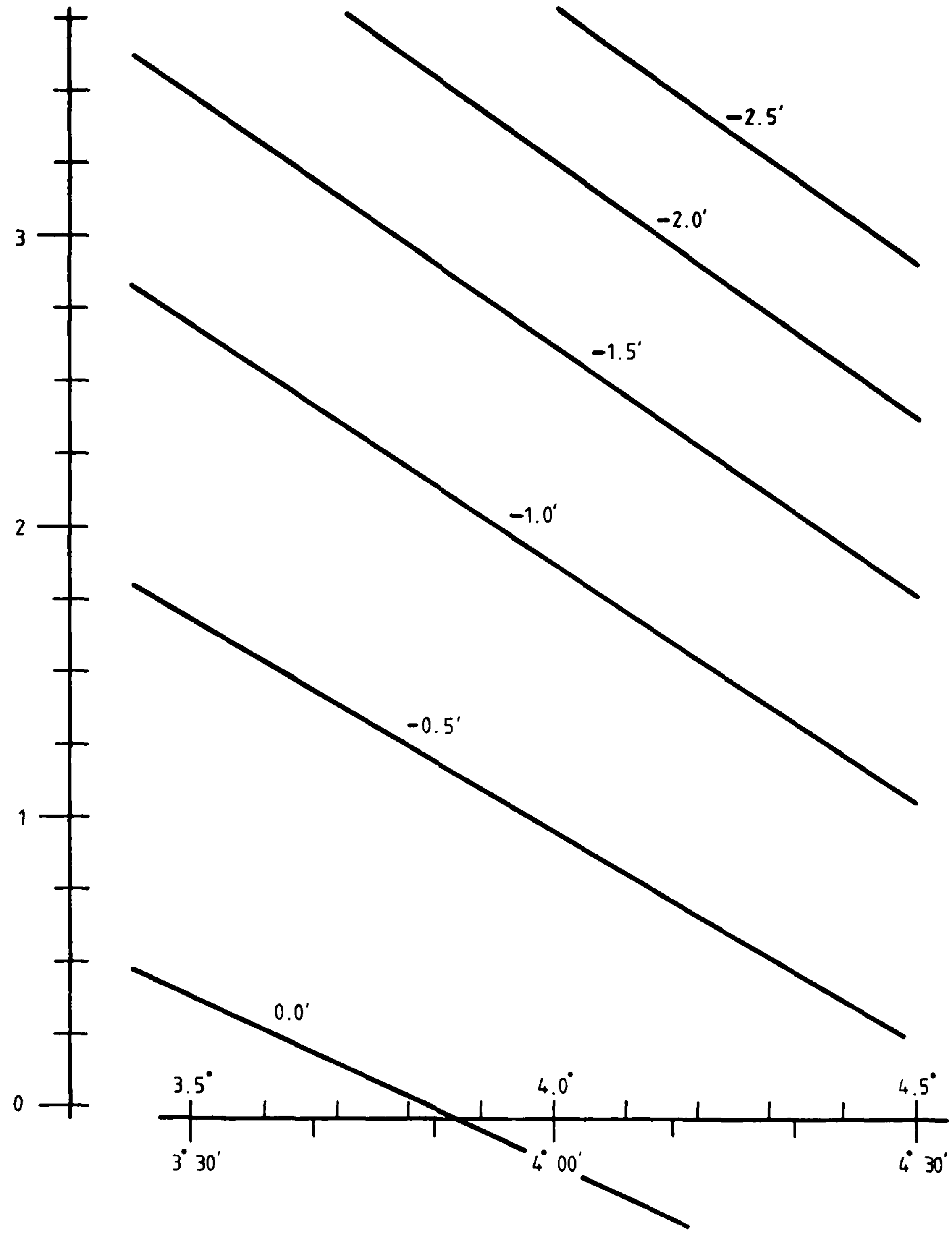


FIG. 26 ELEVATION CORRECTIONS REQUIRED FOR CONSISTENCY WITH POLE CHECKS, A – 4G CONDITIONS.

at finite elevations, as shown in Figure 24. This is, however, not the complete story. At a fixed distance aft of the mirror, the slant range from the mirror to the offset point of observation is greater than that on the central plane, due to the 45 ft offset distance. The increased slant range more than compensates for the reduction in vertical angle and results in an increased height above the deck plane. This is illustrated in Figure 19.

While these combined effects are quite small and not sufficient to be noticeable by pilots on approach, they are sufficient to influence pole checks where accuracies better than 1 minute of arc (or about 1 in. in pole height) are being sought. The errors are systematic and calculable, but the method of calculation is indirect and tedious.

It is necessary to determine, for all possible settings of the mirror, either

(*a*) the corrections/errors in pole heights corresponding to the theoretical settings; or

(*b*) the corrections/errors in mirror settings that correspond to the nominal pole heights.

The latter method has been used with mirror height setting preserved and the errors calculated as corrections/errors in elevation settings. An error plot can then be generated for the domain of representation used in Figures 14 and 15.

In Section 9 the three-dimensional problem was solved directly by specifying the point of reflection on the mirror and thence determining the reflected ray. By comparison it is now required to specify a point (pole check position) through which the reflected ray must pass, and thence to determine the required point of reflection and elevation setting. This requires a convergent iterative procedure.

The procedure commences with the fixed position of the source lights, the assigned "pole check" position and an approximate (assumed) point of reflection. The angle between the incident and reflected rays is bisected to obtain an estimate of the direction of the normal to the mirror surface, and that in turn provides both a revised estimate of the point of reflection and an estimate of the elevation setting. The procedure is then repeated to obtain a stable self-consistent solution. The relevant equations are given in Appendix B.

The values for elevation angle obtained by this method are then compared with the equivalent "theoretical" (two-dimensional) values obtained as in Section 3 to obtain the corrections/errors. Finally the discrete errors are interpolated to produce error loci. The results are plotted in Figure 25 (S-2E) and Figure 26 (A-4G).

The worst-case errors are about 2·5 minutes of arc in the region of No. 5 wire. The polarity of the error (shown as negative in Figures 25 and 26) is such that the elevation setting required for the pole check to be correct is less than the theoretical value. With the theoretical setting the image will appear slightly below the datum line. Alternatively the pole height needed to obtain a correct check with the theoretical setting of elevation would have to be greater than nominal. The requisite height increase at the distance appropriate to No. 5 wire is about 2·8 in.

Although these corrections/errors are quite small they are comparable with the scale graduation units for the mirror settings in either elevation or height. They are also significantly larger than the variations in flight deck level.

More importantly, they provide some indication as to the significance of local errors in the mirror surface. As previously stated (Section 8) a set of clinometer measurements made on the lateral centre-line of the mirror reputedly showed a progressive change, from centre to port edge, of 7 minutes of arc. Such *in situ* measurements would, however, be influenced by any residual ship pitch or roll and by any elevation of the mirror. The precise conditions of measurement are not known to the author.

11. CONCLUSIONS

A description of the Mirror Deck Landing Aid, its installation details and performance, have been given in the preceding sections.

Operational settings for the mirror are currently calculated for specific conditions of glide slope, arrestor wire and aircraft type, and are then tabulated for operational use. The underlying relationships can be represented in graphical form. When prepared as a set of overlays, a composite representation can be obtained for any particular hook-to-eye height, which provides information on all possible settings of mirror height and elevation.

The mechanisms for height setting and for elevation setting and stabilisation involve servos and gear trains that require periodic maintenance. It is likely that on reassembly of the mechanisms the previously existing "zero" settings may not be restored, thus giving rise to the significant discrepancies in settings that have been apparent from time to time.

A calibration procedure is described which enables the "zero" settings to be measured on the height and elevation scales, thus avoiding both the scale zero errors and the potential build-up of measurement and reading errors that can arise from the use of gravity-referenced theodolites for calibration. The procedure is sufficiently simple that it should be possible for ship's crew to perform datum and calibration checks at sea as well as pole checks.

Apart from gross changes of datum values for whatever reason, the source of potentially greatest error is likely to be in the accuracy of the mirror surface. Ideally, deviations from the perfect cylindrical surface should be less than 1 minute of arc, but it is likely that local areas of the surface will deviate by several minutes of arc particularly towards the outer edges.

In practice it is the centre portion of the mirror that generates the image for all but the final stages of an approach, whereas pole checks on the angle centre-line use the port edge of the mirror. The calibration procedure described uses a sighting position as far to port as practicable and thus a point of reflection closer to the centre of the mirror, thus being more relevant to the dominant portion of an aircraft approach.

REFERENCES

1. Drg. No. 845/51, Sht 3, 30 January 1969: "HMAS *Melbourne* Extended Refit 1968, General Arrangement (as fitted) 1 Deck". (Confidential)

2. GMGID letter DNC 20-14-92 (undated, circa July 1976) to DMED and DNAP: "HMAS *Melbourne*—Mirror Deck Landing Aid—Mirror Settings." (Restricted) plus Enclosures.

APPENDIX A

Calculation of Coverage Diagram

1. Methodology

The method used is that of ray path calculation based on a point source and a nominated point of reflection on the mirror surface. Sweeping the point of reflection across the face of the mirror, laterally and vertically, generates the spatial coverage for a particular combination of mirror settings and ship pitch and roll.

To accommodate the various axes of movement, etc., a set of axis systems must be defined in which each particular angle may be conveniently defined. The coverage diagram is to be presented in an axis system with origin in the sea surface and moving with the ship. The computation commences with a ship-oriented axis system with origin at the centre of the mirror surface and with the known co-ordinates, within that system, of the source lights. The axis system is then, by translations and rotations, aligned with a system having its longitudinal axis coinciding with the normal to the mirror surface at the nominated point of reflection. The reflected ray is identified in this axis system by the sign change of the y and z co-ordinates of the source lights. This point on the reflected ray, together with the point of reflection, identifies the reflected ray. the two points identifying the ray are then tracked through axis rotations and translations into the earth axis system. The ray is then extrapolated to intercept any particular surface of representation.

2. Axis Systems

2.1 Ship referenced system {S}

Origin: "centre" of pitch and roll,
X_S, longitudinal, positive aft,
Y_S, lateral, positive starboard,
Z_S, up–down, positive upwards.

2.2 "Earth" referenced system {E1}

Coincident with {S} for zero ship pitch and roll.
Origin: "centre" of pitch and roll,
X_{E1}, horizontal along, positive aft,
Y_{E1}, horizontal across, positive starboard,
Z_{E1}, vertical, positive upwards.

2.3 "Sea" referenced system {E0}

Translation of system {E1} horizontally forward (by 26 ft) and vertically downward (by 6 ft) to position the origin at midships (for zero ship pitch and roll) and at the waterline.
Origin: "midships" at the waterline,
X_{E0}, parallel to X_{E1}.
Y_{E0}, parallel to Y_{E1}.
Z_{E0}, parallel to Z_{E1}.

2.4 Mirror referenced systems

2.4.1 System {M1}

Translation of system {S} longitudinally aft (by 24 ft), laterally port (by 62·858 ft) and upwards (by $31 \cdot 5' - H_D + H_0 + H_S$) to position the origin at the centre of the mirror surface.

Origin: centre of the mirror surface,

X_{M1}, parallel to X_S,
Y_{M1}, parallel to Y_S,
Z_{M1}, parallel to Z_S.

2.4.2 System {M2}

Rotation of system {M1} azimuthally (by 1·5 degrees) to orthogonality of mirror framework and with lateral axis coincident with axis of elevation of the mirror.

Origin: centre of mirror aperture,

X_{M2}, "longitudinal", positive aft,
Y_{M2}, "lateral", positive starboard,
Z_{M2}, up–down, positive upwards (coincident with Z_{M1}).

2.4.3 System {M3}

Rotation of system {M2} in elevation (by $\beta_0 - \beta_S - \frac{1}{2}\theta$) to align yz axes (plane $x = 0$) with the plane of the mirror aperture.

Origin: centre of mirror surface,

X_{M3}, "longitudinal", positive aft,
Y_{M3}, "lateral", positive starboard (coincident with Y_{M2}),
Z_{M3}, "up–down", positive upwards.

2.4.4 System {M4}

Translation of system {M3} longitudinally (by 10 ft) to position the origin on the axis of curvature of the mirror in the mid-plane.

Origin: on axis of curvature, mid-plane,

X_{M4}, parallel to X_{M3},
Y_{M4}, parallel to Y_{M3},
Z_{M4}, parallel to Z_{M3} (axis of curvature).

2.4.5 System {M5}

Translation of system {M4} up–down (by d') along the axis of curvature to the desired "high/low ball" level for vertical coverage.

Origin: on axis of curvature, high/low,

X_{M5}, parallel to X_{M4},
Y_{M5}, parallel to Y_{M4},
Z_{M5}, parallel to Z_{M4} (axis of curvature).

$-2 \leqslant d \leqslant +2$.

2.4.6 System {M6}

Rotation of system {M5} in azimuth (by χ degrees) about the axis of curvature to set the desired ray path reflection point for azimuthal coverage.

Origin: on axis of curvature, high low,

X_{M6}, "longitudinal", positive aft,
Y_{M6}, "lateral", positive starboard,
Z_{M6}, "up down", positive upwards (coincident with Z_{M5}).

$-14 \cdot 5 \leqslant \chi \leqslant +14 \cdot 5$.

2.4.7 System {M7}

Translation of system {M6} longitudinally (by -10 degrees) to position the origin at the desired point of reflection on the surface of the mirror.

Origin: point of reflection on the mirror,

X_{M7}, parallel to X_{M6},
Y_{M7}, parallel to Y_{M6},
Z_{M7}, parallel to Z_{M6}.

3. Datum Points

M	Centre of mirror surface, origin of {M1}, {M2}, {M3}.
S	Source light (single point).
Q	Point of reflection on mirror surface, origin of {M7}.
R	Reference point on reflected ray.
C	"Centre" of pitch and roll, origin of {S}, {E1}.
O	"Midships" on the waterline, origin of {E0}.

4. Incident Ray

The incident ray is defined by points S and Q. The co-ordinates of these two points in axis system {M7} are:

S $\quad (S_{M7}) \equiv ({}_{S}X_{M7},\ {}_{S}Y_{M7},\ {}_{S}Z_{M7})$

Q $\quad (Q_{M7}) \equiv ({}_{Q}X_{M7},\ {}_{Q}Y_{M7},\ {}_{Q}Z_{M7}) \equiv (0, 0, 0)$.

5. Reflected Ray

The reflected ray is defined by points Q and R where R is defined in axis system {M7} as

R $\quad (R_{M7}) \equiv ({}_{R}X_{M7},\ {}_{R}Y_{M7},\ {}_{R}Z_{M7}) \equiv ({}_{S}X_{M7},\ -{}_{S}Y_{M7},\ -{}_{S}Z_{M7})$.

6. Procedure

The co-ordinates of S in {S} are known, viz:

$$\begin{aligned}(S_S) &\equiv ({}_{S}X_S,\ {}_{S}Y_S,\ {}_{S}Z_S)\\ &= (-24' + 139' \cos 5{\cdot}85^\circ,\ -62{\cdot}858' - 139' \sin 5{\cdot}85^\circ,\ 31{\cdot}5' + 0{\cdot}75')\\ &= (-24' + 139{\cdot}276',\ -62{\cdot}858' - 14{\cdot}167',\ 32{\cdot}25')\\ &= (162{\cdot}276',\ -48{\cdot}701',\ 32{\cdot}25')\end{aligned}$$

and by translation {S} → {M1} the co-ordinates of s in {M1} are also known, viz.:

$$\begin{aligned}(S_{M1}) &\equiv ({}_{S}X_{M1},\ {}_{S}Y_{M1},\ {}_{S}Z_{M1})\\ &= (139 \cos 5{\cdot}85^\circ,\ 139 \sin 5{\cdot}85^\circ,\ -H_0 - H_S)\\ &= (138{\cdot}276',\ 14{\cdot}167',\ 2'' - H_S)\,.\end{aligned}$$

Transform (S_{M1}) through the transformations:

$$\{M1\} \to \{M2\} \to \{M3\} \to \{M4\} \to \{M5\} \to \{M6\} \to \{M7\}$$

to yield

$$(S_{M7}) \equiv ({}_{S}X_{M7},\ {}_{S}Y_{M7},\ {}_{S}Z_{M7})\,.$$

Define

$$(Q_{M7}) \equiv ({}_{Q}X_{M7},\ {}_{Q}Y_{M7},\ {}_{Q}Z_{M7}) \equiv (0, 0, 0)$$

$$(R_{M7}) \equiv ({}_{R}X_{M7},\ {}_{R}Y_{M7},\ {}_{R}Z_{M7}) \equiv ({}_{S}X_{M7},\ -{}_{S}Y_{M7},\ -{}_{S}Z_{M7})\,.$$

Transform (Q_{M7}), (R_{M7}) through transformations:

$$\{M7\} \to \{M6\} \to \{M5\} \to \{M4\} \to \{M3\} \to \{M2\} \to \{M1\} \to \{S\} \to \{E1\} \to \{E0\}\,.$$

The reflected ray is then defined in the "Sea" referenced axis system {E0} by the two points

$$(Q_{E0}) \equiv ({}_{Q}X_{E0},\ {}_{Q}Y_{E0},\ {}_{Q}Z_{E0})$$

$$(R_{E0}) \equiv ({}_{R}X_{E0},\ {}_{R}Y_{E0},\ {}_{R}Z_{E0})\,.$$

Points on the reflected ray can then be found by extrapolation along the ray path QR to the intersection with any required surface of representation.

Two useful surfaces for representation are:

(*a*) a vertical plane surface at fixed distance aft of the ship, defined by

$$X_{E0} = \text{constant} \; ;$$

(*b*) a vertical cylindrical surface at fixed radial distance from the ship, defined by

$$X_{E0}^2 + Y_{E0}^2 = \text{constant} \, .$$

The general point P on the ray path is given by

$$(P_{E0}) \equiv ({}_PX_{E0},\ {}_PY_{E0},\ {}_PZ_{E0})$$

with

$$\frac{{}_PX_{E0} - {}_QX_{E0}}{{}_RX_{E0} - {}_QX_{E0}} = \frac{{}_PY_{E0} - {}_QY_{E0}}{{}_RY_{E0} - {}_QY_{E0}} = \frac{{}_PZ_{E0} - {}_QZ_{E0}}{{}_RZ_{E0} - {}_QZ_{E0}} \, .$$

For intersections with a vertical plane at distance K_1 aft of the ship, ${}_PX_{E0} = K_1$ and the y and z co-ordinates of the intersection are given by:

$${}_PY_{E0} = {}_QY_{E0} + ({}_RY_{E0} - {}_QY_{E0}) \frac{(K_1 - {}_QX_{E0})}{({}_RX_{E0} - {}_QX_{E0})}$$

$${}_PZ_{E0} = {}_QZ_{E0} + ({}_RZ_{E0} - {}_QZ_{E0}) \frac{(K_1 - {}_QX_{E0})}{({}_RY_{E0} - {}_QX_{E0})} \, .$$

For intersections with a vertical cylinder at radius K_2 from the ship, substitute

$${}_PY_{E0} = {}_QY_{E0} - ({}_RY_{E0} - {}_QY_{E0}) \frac{({}_PX_{E0} - {}_QX_{E0})}{({}_RX_{E0} - {}_QX_{E0})}$$

into

$$({}_PX_{E0})^2 - ({}_PY_{E0})^2 = K_2^2$$

to obtain a quadratic in ${}_PX_{E0}$ from which the positive root is required. Knowing ${}_PX_{E0}$ solve for y and z co-ordinates as previously. For this case with three dimensions it is more convenient to plot azimuth offset (from the axial centre-line) together with height in a $({}_PX_{E0},\ {}_PZ_{E0})$ plot using

$${}_P\chi_{E0} = \tan^{-1}[{}_PY_{E0}/{}_PX_{E0}] \, .$$

7. *Transformations*

7.1 $\{E0\} \leftrightarrow \{E1\}$

Sea datum to centre of pitch and roll:
horizontal aft 26 ft,
vertical upwards 6 ft.

$$\{E0\} \rightarrow \{E1\} \qquad \begin{bmatrix} X_{E1} \\ Y_{E1} \\ Z_{E1} \end{bmatrix} = \begin{bmatrix} X_{E0} \\ Y_{E0} \\ Z_{E0} \end{bmatrix} - \begin{bmatrix} -26 \\ 0 \\ -6 \end{bmatrix} \qquad\qquad \{E1\} \rightarrow \{E0\} \qquad \begin{bmatrix} X_{E0} \\ Y_{E0} \\ Z_{E0} \end{bmatrix} = \begin{bmatrix} X_{E1} \\ Y_{E1} \\ Z_{E1} \end{bmatrix} + \begin{bmatrix} -26 \\ 0 \\ -6 \end{bmatrix} \, .$$

7.2 $\{E1\} \leftrightarrow \{S\}$

Ship pitch and roll, refer Figure A1.
ship pitch, θ, positive bow up,
ship roll, ϕ, positive roll to starboard about the pitched longitudinal axis.

7.2.1 $\{E1\} \leftrightarrow \{E1'\}$

Ship pitch, θ

$$\{E1\} \rightarrow \{E1'\} \qquad \begin{bmatrix} X_{E1'} \\ Y_{E1'} \\ Z_{E1'} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} X_{E1} \\ Y_{E1} \\ Z_{E1} \end{bmatrix} \qquad\qquad \{E1'\} \rightarrow \{E1\} \qquad \begin{bmatrix} X_{E1} \\ Y_{E1} \\ Z_{E1} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} X_{E1'} \\ Y_{E1'} \\ Z_{E1'} \end{bmatrix} \, .$$

7.2.2 {E1'} ↔ {S}

Ship roll, ϕ

$$\{E1'\} \rightarrow \{S\}: \quad \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} X_{E1'} \\ Y_{E1'} \\ Z_{E1'} \end{bmatrix}$$

$$\{S\} \rightarrow \{E1'\}: \quad \begin{bmatrix} X_{E1'} \\ Y_{E1'} \\ Z_{E1'} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} .$$

7.3 {S} ↔ {M1}

Centre of pitch and roll to mirror position:
Longitudinal aft 24′,
lateral port 62·858′,
upwards $31\cdot5' - H_D - H_0 + H_S$.
$H_D = -9''\ (-0\cdot75')$
$H_0 = -2''\ (-0\cdot167')$

$$\{S\} \rightarrow \{M1\}: \quad \begin{bmatrix} X_{M1} \\ Y_{M1} \\ Z_{M1} \end{bmatrix} = \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} - \begin{bmatrix} +24 \\ -62\cdot858 \\ -32\cdot083 - H_S \end{bmatrix}$$

$$\{M1\} \rightarrow \{S\}: \quad \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = \begin{bmatrix} X_{M1} \\ Y_{M1} \\ Z_{M1} \end{bmatrix} - \begin{bmatrix} -24 \\ -62\cdot858 \\ -32\cdot083 \cdot H_S \end{bmatrix} .$$

7.4 {M1} ↔ {M2}

Rotation γ in azimuth to mirror orientation refer Figure A2.
$\gamma \quad 1\cdot5$

$$\{M1\} \rightarrow \{M2\}: \quad \begin{bmatrix} X_{M2} \\ Y_{M2} \\ Z_{M2} \end{bmatrix} \quad \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{M1} \\ Y_{M1} \\ Z_{M1} \end{bmatrix}$$

$$\{M2\} \rightarrow \{M1\}: \quad \begin{bmatrix} X_{M1} \\ Y_{M1} \\ Z_{M1} \end{bmatrix} = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{M2} \\ Y_{M2} \\ Z_{M2} \end{bmatrix} .$$

7.5 {M2} ↔ {M3}

Rotation β_M in elevation to mirror elevation, refer Figure A3.
$\beta_M \quad \beta_0 \quad \beta_S \quad \frac{1}{2}\theta$
$\beta_0 \quad 1\cdot5$

$$\{M2\} \rightarrow \{M3\}: \quad \begin{bmatrix} X_{M2} \\ \\ Z_{M3} \end{bmatrix} \quad \begin{bmatrix} \cos\beta_M & 0 & \sin\beta_M \\ 0 & 1 & 0 \\ \sin\beta_M & 0 & \cos\beta_M \end{bmatrix} \begin{bmatrix} X_{M2} \\ Y_{M2} \\ Z_{M2} \end{bmatrix}$$

$$\{M3\} \rightarrow \{M2\}: \quad \begin{bmatrix} X_{M2} \\ Y_{M2} \\ Z_{M2} \end{bmatrix} \quad \begin{bmatrix} \cos\beta_M & 0 & \sin\beta_M \\ 0 & 1 & 0 \\ \sin\beta_M & 0 & \cos\beta_M \end{bmatrix} \begin{bmatrix} X_{M3} \\ Y_{M3} \\ Z_{M3} \end{bmatrix} .$$

7.6 $\{M3\} \leftrightarrow \{M4\}$

Translation longitudinally 10 ft aft to axis of curvature.

$\{M3\} \rightarrow \{M4\}$ $\qquad\qquad$ $\{M4\} \rightarrow \{M3\}$

$$\begin{bmatrix} X_{M4} \\ Y_{M4} \\ Z_{M4} \end{bmatrix} = \begin{bmatrix} X_{M3} \\ Y_{M3} \\ Z_{M3} \end{bmatrix} - \begin{bmatrix} 10 \\ 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} X_{M3} \\ Y_{M3} \\ Z_{M3} \end{bmatrix} = \begin{bmatrix} X_{M4} \\ Y_{M4} \\ Z_{M4} \end{bmatrix} + \begin{bmatrix} 10 \\ 0 \\ 0 \end{bmatrix}.$$

7.7 $\{M4\} \leftrightarrow \{M5\}$

Translation up–down d ft for "high/low ball," positive d for high ball.
Family of values 0, $\pm 1{\cdot}25$, $\pm 2{\cdot}5$ ft.
$\pm 2{\cdot}5$ ft correspond to top and bottom edge of mirror.

$\{M4\} \rightarrow \{M5\}$ $\qquad\qquad$ $\{M5\} \rightarrow \{M4\}$

$$\begin{bmatrix} X_{M5} \\ Y_{M5} \\ Z_{M5} \end{bmatrix} = \begin{bmatrix} X_{M4} \\ Y_{M4} \\ Z_{M4} \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ d \end{bmatrix} \qquad \begin{bmatrix} X_{M4} \\ Y_{M4} \\ Z_{M4} \end{bmatrix} = \begin{bmatrix} X_{M5} \\ Y_{M5} \\ Z_{M5} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ d \end{bmatrix}.$$

7.8 $\{M5\} \leftrightarrow \{M6\}$

Rotation χ in azimuth to set desired point of reflection, refer Figure A4.

$\{M5\} \rightarrow \{M6\}$ $\qquad\qquad$ $\{M6\} \rightarrow \{M5\}$

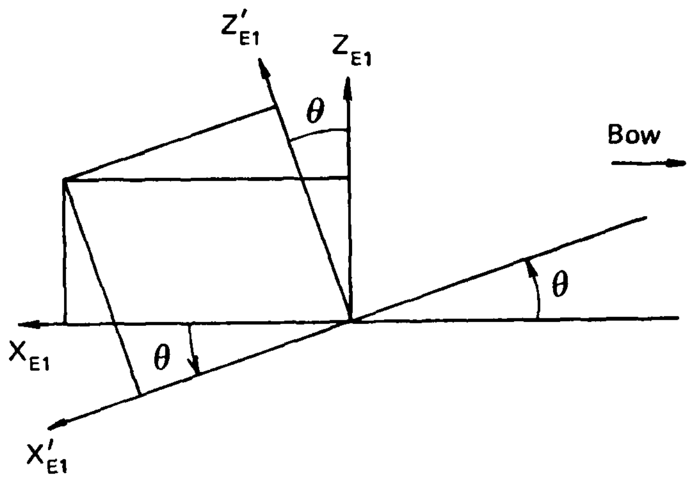
$$\begin{bmatrix} X_{M6} \\ Y_{M6} \\ Z_{M6} \end{bmatrix} = \begin{bmatrix} \cos\chi & \sin\chi & 0 \\ -\sin\chi & \cos\chi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{M5} \\ Y_{M5} \\ Z_{M5} \end{bmatrix} \qquad \begin{bmatrix} X_{M5} \\ Y_{M5} \\ Z_{M5} \end{bmatrix} = \begin{bmatrix} \cos\chi & -\sin\chi & 0 \\ \sin\chi & \cos\chi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{M6} \\ Y_{M6} \\ Z_{M6} \end{bmatrix}.$$

7.9 $\{M6\} \leftrightarrow \{M7\}$

Translation 10 ft longitudinally to set origin at the point of reflection.

$\{M6\} \rightarrow \{M7\}$ $\qquad\qquad$ $\{M7\} \rightarrow \{M6\}$

$$\begin{bmatrix} X_{M7} \\ Y_{M7} \\ Z_{M7} \end{bmatrix} = \begin{bmatrix} X_{M6} \\ Y_{M6} \\ Z_{M6} \end{bmatrix} - \begin{bmatrix} -10 \\ 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} X_{M6} \\ Y_{M6} \\ Z_{M6} \end{bmatrix} = \begin{bmatrix} X_{M7} \\ Y_{M7} \\ Z_{M7} \end{bmatrix} + \begin{bmatrix} -10 \\ 0 \\ 0 \end{bmatrix}.$$

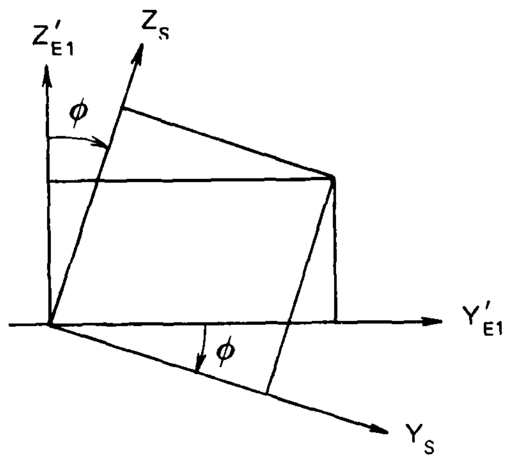


$$X'_{E1} = X_{E1}\ \mathrm{Cos}\ \theta - Z_{E1}\ \mathrm{Sin}\ \theta$$

$$Y'_{E1} = Y_{E1}$$

$$Z'_{E1} = Z_{E1}\ \mathrm{Cos}\ \theta + Y_{E1}\ \mathrm{Sin}\ \theta$$

(a) Ship pitch



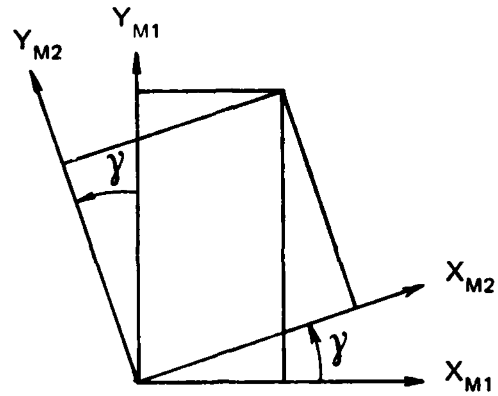
$$X_S = X'_{E1}$$

$$Y_S = Y'_{E1}\ \mathrm{Cos}\,\phi - Z'_{E1}\,\mathrm{Sin}\,\phi$$

$$Z\ = Z'_{E1}\ \mathrm{Cos}\ \phi + Y'_{E1}\ \mathrm{Sin}\,\phi$$

(b) Ship roll

FIG. A1 TRANSFORMATION {E1} – {S}

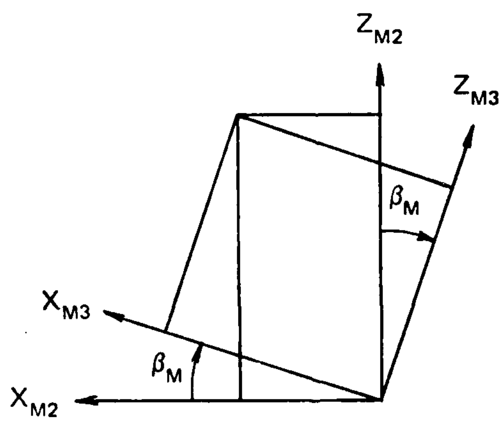


$$X_{M2} = X_{M1} \text{ Cos } \gamma + Y_{M1} \text{ Sin } \gamma$$

$$Y_{M2} = Y_{M1} \text{ Cos } \gamma - X_{M1} \text{ Sin } \gamma$$

$$Z_{M2} = Z_{M1}$$

FIG. A2 TRANSFORMATION {M1} – {M2}

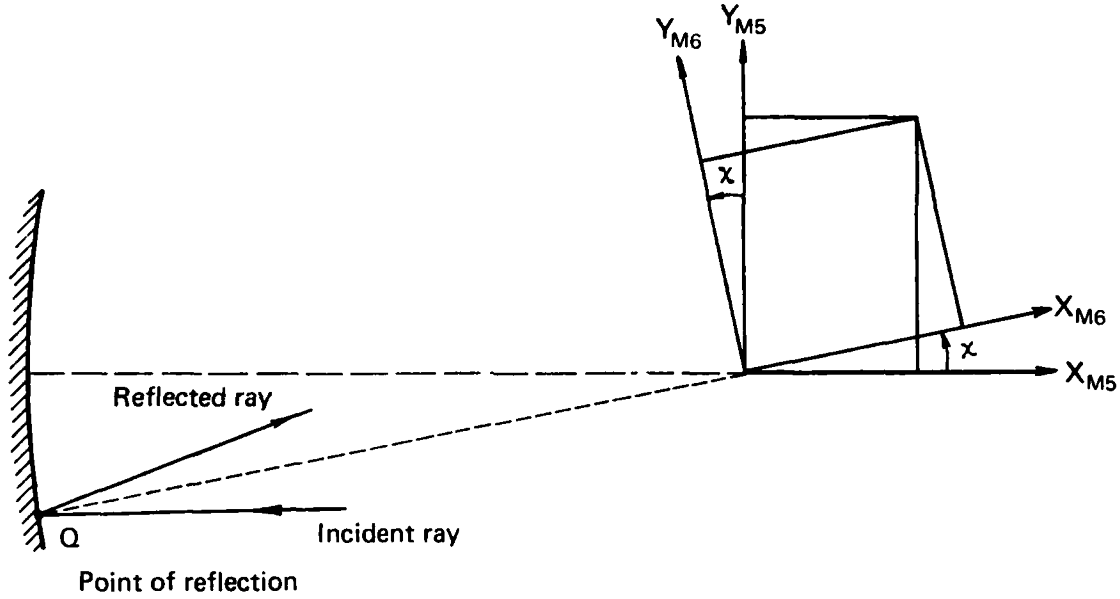


$$X_{M3} = X_{M2} \text{ Cos}\beta_M + Z_{M2} \text{ Sin } \beta_M$$

$$Y_{M3} = Y_{M2}$$

$$Z_{M3} = Z_{M2} \text{ Cos } \beta_M - Y_{M2} \text{ Sin } \beta_M$$

FIG. A3 TRANSFORMATION {M2} – {M3}



$$X_{M6} = X_{M5} \cos\chi + Y_{M5} \sin\chi$$

$$Y_{M6} = Y_{M5} \cos\chi - X_{M5} \sin\chi$$

$$Z_{M6} = Z_{M5}$$

FIG. A4 TRANSFORMATION {M5} – {M6}

APPENDIX B

Effect of Lateral Offset

1. Methodology

As in Appendix A the method used is one relating to ray path calculation; however, the inverse problem is required to be solved and a different technique is used. In Appendix A the point of reflection on the mirror surface and the direction of the normal at that point were specified parametrically, allowing the reflected ray to be calculated directly. For the inverse case a point on the reflected ray is specified and the appropriate point of reflection must be determined.

The procedure used is an iterative process commencing with the fixed position of the source lights, the assigned point on the reflected ray (pole position) and a rough estimate of the point of reflection. Incident and reflected rays are thus ascribed. The angle between the rays is bisected to obtain an estimate of the direction of the normal to the mirror surface at the point of reflection. This in turn is used to obtain a revised estimate of the point of reflection. The procedure is repeated to obtain a stable self-consistent solution. The solution provides the required mirror elevation.

2. Axis Systems

For convenience, two mirror-referenced axis systems are useful for defining the calculation procedure.

2.1 Mirror referenced system {M8}

Origin: centre of the mirror surface.

X_{M8}, longitudinal, positive aft parallel to angle centre-line,

Y_{M8}, lateral, positive starboard,

Z_{M8}, up–down, positive upwards,

$Z_{M8} = 0$, plane parallel to deck plane.

The source lights, taken as a single point source, thus lie(s) in the plane $Y = 0$. Note also that system {M8} is equivalent to the rotation of system {M1} (Appendix A) azimuthally by 5·85 degrees, or system {M2} by 4·35 degrees. The mirror framework, i.e. central vertical plane and axis of elevation, is offset from the axis system {M8} by −4·35 degrees in azimuth.

2.2 Mirror referenced system {M9}

Translation of system {M8} to the estimated point of reflection on the mirror surface (updated at each iteration).

Origin: estimated point of reflection on mirror.

X_{M9}, parallel to X_{M8},

Y_{M9}, parallel to Y_{M8},

Z_{M9}, parallel to Z_{M8}.

3. *Datum Points*

- M centre of mirror surface,
- S source light (single point),
- Q point of reflection on mirror surface.
- P pole position (point on reflected ray),
- R reference point on reflected ray QP such that $|QR| = |QS|$,
- N reference point on the normal to the mirror surface at the point of reflection (mid-point of SR),
- C centre of curvature of mirror section through its lateral centre-line.

A superscript, i.e. Q^i, R^i, N^i, is used to denote the estimated values at the *i*th iteration.

4. *Incident Ray*

The incident ray SQ is approximated by the points S and Q^i. With the mirror height setting at H_S the co-ordinates of these two points in axis system {M8} are:

$$S : (S_{M8}) \equiv ({}_SX_{M8}, {}_SY_{M8}, {}_SZ_{M8})$$
$$= (D_L, 0, -H_S - H_0)$$
$$Q^i : (Q^i_{M8}) \equiv ({}_QX^i_{M8}, {}_QY^i_{M8}, {}_QZ^i_{M8})$$
$$= (\Delta x^i, \Delta y^i, \Delta z^i)$$

with

$$Q^0 = (0, 0, 0)$$

and

$$Q^i \to Q = (\Delta x, \Delta y, \Delta z)$$

as the iteration converges.

5. *Reflected Ray*

The reflected ray QP is approximated by the points Q^i and P where P has co-ordinates in system {M8} of:

$$P : (P_{M8}) \equiv ({}_PX_{M8}, {}_PY_{M8}, {}_PZ_{M8})$$
$$= (D_T, 45, -H_S - H_0 - H_D - H_Y) .$$

6. *Procedure*

The co-ordinates of S and P in {M8} are known and constant. With translation {M8} → {M9} the estimated ray paths are defined by Q^i, the origin of {M9} and the points:

$$S : (S_{M9}) \equiv ({}_SX^i_{M9}, {}_SY^i_{M9}, {}_SZ^i_{M9})$$
$$= (D_L - \Delta x^i, -\Delta y^i, -H_0 - H_S - \Delta z^i)$$

and

$$P : (P_{M9}) \equiv ({}_PX^i_{M9}, {}_PY^i_{M9}, {}_PZ^i_{M9})$$
$$= (D_T - \Delta x^i, 45 - \Delta y^i, -H_0 - H_S - H_D - H_Y - \Delta z^i) .$$

The point R^i on Q^iP at distance equal to $|Q^iS|$ is obtained by scaling, viz :

$$R^i : (R^i_{M9}) \equiv ({}_RX^i_{M9}, {}_RY^i_{M9}, {}_RZ^i_{M9})$$
$$= (k\,{}_PX^i_{M9}, k\,{}_PY^i_{M9}, k\,{}_PZ^i_{M9})$$

where

$$k = \frac{[({}_SX^i_{M9})^2 + ({}_SY^i_{M9})^2 + ({}_SZ^i_{M9})^2]^{\frac{1}{2}}}{[({}_PX^i_{M9})^2 + ({}_PY^i_{M9})^2 + ({}_PZ^i_{M9})^2]^{\frac{1}{2}}} .$$

The mid-point of SR^i is the point N^i lying nominally on the normal to the mirror surface at the point of reflection Q^i. That normal should pass through C.

The line Q^iN^i provides estimates of the azimuth and elevation, in system {M9}, of the normal. A line parallel to Q^iN^i passing through C provides a revised estimate Q^{i+1} with which to re-enter the process.

With reference to Figures 24 and B1 the required relationships are given below.

$$2\begin{bmatrix} {}_NX^i{}_{M9} \\ {}_NY^i{}_{M9} \\ {}_NZ^i{}_{M9} \end{bmatrix} = \begin{bmatrix} {}_SX^i{}_{M9} \\ {}_SY^i{}_{M9} \\ {}_SZ^i{}_{M9} \end{bmatrix} + \begin{bmatrix} {}_RX^i{}_{M9} \\ {}_RY^i{}_{M9} \\ {}_RZ^i{}_{M9} \end{bmatrix}$$

$$\tan(\psi^i{}_e - 4\cdot 35) = ({}_NY^i{}_{M9}/{}_NX^i{}_{M9})$$

giving

$$\psi^i{}_e = \tan^{-1}[{}_NY^i{}_{M9}/{}_NX^i{}_{M9}] + 4\cdot 35$$

$$\tan\beta^i{}_e = {}_NZ^i{}_{M9}/[({}_NX^i{}_{M9})^2 + ({}_NY^i{}_{M9})^2]^{\frac{1}{2}}$$

$$\cos\psi^i \sin\beta^i = \sin\beta^i{}_e$$

$$\cos\psi^i \cos\beta^i = \cos\beta^i{}_e \cos\psi^i{}_e$$

giving

$$\beta^i = \tan^{-1}[\tan\beta^i{}_e/\cos\psi^i{}_e]\ .$$

Using this estimate, β^i, for the elevation of the mirror, together with the $4\cdot 35$ degree azimuth offset of the axis of elevation, the estimate for C, the centre of curvature, in system {M8} is then:

$$\begin{bmatrix} {}_CX^i{}_{M8} \\ {}_CY^i{}_{M8} \\ {}_CZ^i{}_{M8} \end{bmatrix} = \begin{bmatrix} -\sin\psi_0 & \sin\psi_0 & 0 \\ -\sin\psi_0 & \cos\psi_0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta^i & 0 & -\cos\beta^i \\ 0 & 1 & 0 \\ \sin\beta^i & 0 & \cos\beta^i \end{bmatrix} \begin{bmatrix} 10 \\ 0 \\ 0 \end{bmatrix}$$

$$= 10 \begin{bmatrix} \cos\psi_0 \cos\beta^i \\ -\sin\psi_0 \cos\beta^i \\ \sin\beta^i \end{bmatrix}$$

where

$$\psi_0 = 4\cdot 35\ .$$

The extrapolation to the revised estimate, Q^{i+1}, in system {M8} using the direction of Q^iN^i is then:

$$\begin{bmatrix} \Delta x^{i+1} \\ \Delta y^{i+1} \\ \Delta z^{i+1} \end{bmatrix} = \begin{bmatrix} {}_CX^i{}_{M8} \\ {}_CY^i{}_{M8} \\ {}_CZ^i{}_{M8} \end{bmatrix} - \left(\frac{10}{Q^iN^i}\right) \begin{bmatrix} {}_NX^i{}_{M9} \\ {}_NY^i{}_{M9} \\ {}_NZ^i{}_{M9} \end{bmatrix}$$

where

$$Q^iN^i = [({}_NX^i{}_{M9})^2 + ({}_NY^i{}_{M9})^2 + ({}_NZ^i{}_{M9})^2]^{\frac{1}{2}}\ .$$

Iterating to a steady state solution yields values for β and ψ which may, for purposes of checking, be fed into the direct procedures set out in Appendix A.

More particularly the solution values for β may be compared with the "theoretical" settings dervied from the central vertical plane analysis in Section 2.

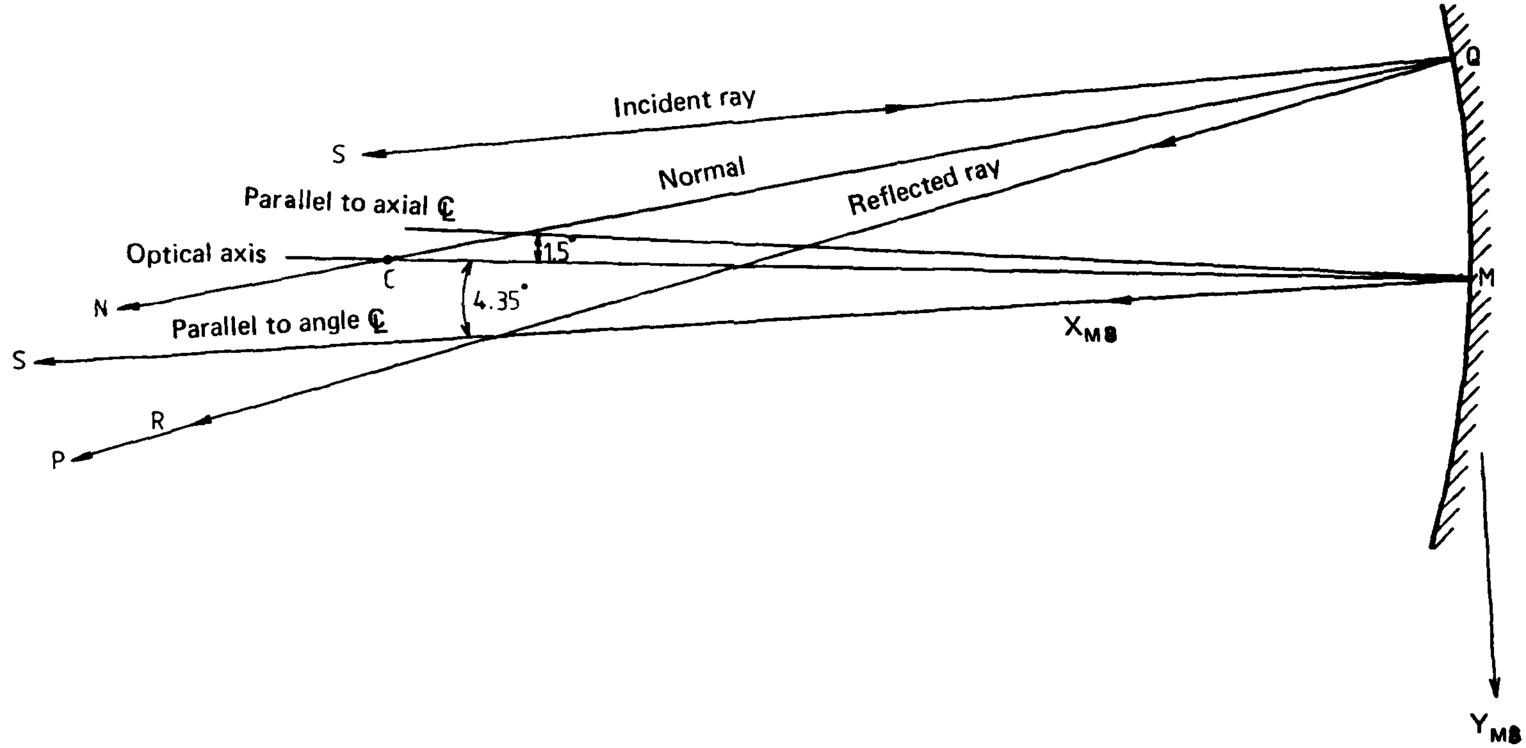


FIG. B1 AZIMUTH GEOMETRY FOR LATERAL OFFSET CALCULATIONS

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16. Abstract

The report provides details of the MDLA system, installation details and calculations concerning performance, coverage, calibration and accuracy requirements. A graphical method of presenting operational settings for height and elevation is described, as also is a simplified technique for calibration.

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